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A FAST HEURISTIC FOR TOMAHWAK LAND-ATTACK PREDESIGNATION

by

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A FAST HEURISTIC FOR TOMAHAWK LAND-ATTACK PREDESIGNATION

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ABSTRACT

The Tomahawk Land-Attack Missile (TLAM) is a lethal, accurate, and long-range weapon that has provided the National Command Authority with the ability to respond with force to crises without committing troops or necessitating a large military build-up. When either the National Command Authority or regional Commander in Chief authorizes the use of TLAMs against specified targets, *predesignation* determines which ship or submarine will fire its missiles at which targets in support of the attack. This thesis presents a fast heuristic to predesignate TLAM target assignments to ships and submarines in multiple battle groups and launch areas over successive time periods. The heuristic allows tasks to be spread or restricted among firing units on a per-target basis, incorporates a variety of task types, and allows all or part of the target list to be manually prioritized. Additionally, the heuristic ensures that better solutions cannot be obtained through a simple, one-complement interchange.

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THESIS DISCLAIMER

The computer programs developed during this research may not have been exercised for all cases of interest. While every effort has been made to ensure that the programs are free of computational and logic errors, they are not considered validated. Any application of these programs without additional verification is at the risk of the user. The Java procedure developed for this research is available from the author or his advisors, but should be requested via Naval Surface Warfare Center, Dahlgren Division, VA.

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LIST OF TERMS AND ABBREVIATIONS

Aimpoint	A two-letter designation used to identify subdivisions of a target. These subdivisions are used to refine impact points for *TLAMs*.
Aircraft Carrier (CV or CVN)	A warship used to launch and retrieve aircraft.
Alignment	The process of preparing a *TLAM* for launch. During alignment, the missile's navigational equipment is energized, the onboard computers are activated, and the software and data are loaded.
Backup Missile	A *TLAM* prepared for launch in order to provide redundancy for *TLAM(s)* designated to attack a target. A *backup missile* must be located on a different ship or submarine than the primary and ready-spare *TLAM(s)* designated to attack the target.
Backup Task Part	A *task part* assigned to a firing unit in order to provide redundancy for a *task part* designating an attack on a target. *Backup task parts* must be executed from *firing units* other than the *firing unit* executing the attack.
Basic Encyclopedia Number (BEN)	An 11-digit alphanumeric code used to designate a target site.
Block	The software and engine combination of a *TLAM*. Currently two *blocks* of Tomahawks are in the inventory. Block II missiles are the original missiles while Block III improvements incorporate *GPS* navigation, improved inertial navigation, and longer range. Block IV missiles will have longer ranges than Block III missiles, a wider variety of unitary warheads, and shortened alignment times.

Capsule Launching System (CLS)	A submarine *TLAM* launching system that provides 12 capsules exclusively for launching TLAMs.
Carrier Battle Group (CVBG)	A group of ships that function as a unit centered on the aircraft carrier, *CV*. A typical *CVBG* consists of up to 10 ships and submarines of varying types.
Cell	The component within a Vertical Launching System that stores missiles, including *TLAMs*.
Commander in Chief (CINC)	The officer in command of a theater of operations, usually a general or flag officer.
Destroyer (DD or DDG)	A warship used as an escort for the aircraft carrier that fills most, but not all, of naval warfare missions. Non-air warfare destroyers are abbreviated *DD*, while air warfare destroyers are abbreviated *DDG*.
Earliest Time to Launch (ETL)	The earliest time a *TLAM* may be launched in order to arrive on target at a specific time.
Expanded Missile Identification (XMID)	An alphanumeric series that provides detailed information about a *TLAM's* capabilities. The *XMID* specifies the most preferred type of *TLAM* to attack a target.
Firing Unit	A ship or submarine that is assigned a *TLAM* task.
Geo-Feasible	*Firing units* that are in a geographical position that enables them to fire *TLAM(s)* at a particular target.
Ghost Missile	A *TLAM* designated to provide attack redundancy for multiple targets.
Ghost Task	A *task* that simultaneously provides redundancy for multiple *tasks* and *task parts*.

Global Positioning System (GPS)	A satellite system that provides navigation information.
Half-module	A four-cell component within the Vertical Launch System. Due to power constraints, each *half-module* can prepare only one land-attack missile at a time.
Hierarchical Restriction (HR)	A method used for solving a multiple-objective mathematical program by expressing the objective function in hierarchical terms, each representing a distinct goal. A separate sub-problem, each consisting of one goal and constraints on superior goals, is solved in decreasing order of priority.
Heuristic Hierarchical Restriction (HHR)	A non-optimal (but generally faster) implementation of hierarchical restriction.
Kit Number	A classification for *TLAM* warheads that do not have high explosive submunitions. The kit number indicates the type of target for that particular warhead.
Latest Time to Launch (LTL)	The latest time a *TLAM* can be launched in order to arrive on target at a specific time.
Launch Area	A large geographic position from which a *TLAM* can be fired and reach the target.
Launch Basket	A location within the launch area where a firing unit may launch its *TLAM*s in order to complete a task.
Launcher	The combination of *VLS modules* onboard a ship. *Launchers* come in two varieties, a full-size *launcher* and a half-size *launcher*. The full-size *launcher* has 61 cells and the half-size *launcher* has 29 cells.

Missile Mission Matching (M^3) List	A prioritized list of *TLAM*s capable of fulfilling a *task*. The first missile on the M^3 list for a *task* is the least capable missile that can perform the *task*.
Mission	A set of three-dimensional coordinates that designates an over-land flight path from a *TLAM*'s point of launch to the target site. A mission defines the target, *aimpoints*, warhead, *block*, and *launch area*.
Mission Identification Number (MID)	An 11-digit serial number designating a *mission*.
Module	The basic component of the *VLS*, consisting of eight *cells*.
National Command Authority (NCA)	The executive branch of government consisting of the President and the Secretary of Defense or their appointed alternates. The *NCA* is responsible for controlling U.S. military forces.
Naval Surface Warfare Center Dahlgren Division (NSWCDD)	A naval command, located in Dahlgren, VA, that conducts research and development on weapon systems.
Planning Size	The maximum number of *task parts* that can simultaneously be assigned to *TLAM*s onboard a *firing unit*.
Predesignation	The process used to determine which ship or submarine will fire Tomahawk missiles during an attack. Predesignation is conducted in two phases. In *Phase 1*, the *TSC* allocates *TLAM* target assignments to ships and submarines. In *Phase 2*, these assignments are allocated to specific *TLAM*s onboard individual ships and submarines based on additional considerations not accounted for in *Phase 1*.
Primary Missile	A *TLAM* designated to be launched at a target.

Primary Task Part	A pre-planned *mission* required by a *firing unit* to prepare a missile for launch against a specific target during a specific interval of clock time. *Primary task parts* include an M^3 list, *Basic Encyclopedia Number*, *Mission Identification*, Aimpoint, *Earliest Time to Launch*, and *Latest Time to Launch.*
Rapid Reprogramming	The ability of a firing unit to change the *mission* without realignment.
Ready-spare Missile	A *TLAM* prepared for launch in order to provide redundancy for *TLAM(s)* designated to attack a target. A *ready-spare missile* must be located on the same ship or submarine as the *TLAM(s)* designated to attack the target.
Ready-spare Task Part	A *task part* assigned to a *firing unit* in order to provide redundancy for a *primary task part. Primary* and *ready-spare task parts* must be assigned to the same *firing unit.*
Salvo Size	The maximum number of *TLAM*s that can simultaneously be *aligned* and launched from a *firing unit.*
SSN	Naval abbreviation for a nuclear submarine.
Strike	A *TLAM* attack consisting of multiple, overlapping *time periods.*
Tactical Tomahawk (TT)	A common name for a Block IV *TLAM*. A Tactical Tomahawk missile will navigate via the *Global Positioning System*, may be reprogrammed during flight, will fly farther than a Block III missile, and will attack mobile targets.
Target List	The entire list of all *TLAM tasks* in a theatre of operations for a given *strike.*
Task	The combination of a *mission* and a *time period.*

Task Part	Components of a task that indicate whether a *TLAM* is to be fired at a target or *aligned* to provide redundancy. *Primary task parts* are fired at the target; *ready-spare task parts* and *backup task parts* provide redundancy for the *primary task part* and are executed in case the *primary task part* fails to reach the target.
Terrain Comparison (TERCOM)	A *TLAM* navigational system which compares the over-flown terrain to a map stored in the missile.
Tomahawk Land Attack Missile (*TLAM*)	A cruise missile fired from ships or submarines capable of striking targets on land.
Time Period	An allowable interval of clock time during which the *TLAM* may be fired to complete a *mission*.
Tomahawk Strike Coordinator (TSC)	The officer responsible for the employment of naval land-attack missiles.
Torpedo Tube	A system used onboard submarines to fire torpedoes or *TLAM*s.
Vertical Launch System (VLS)	A system onboard a surface ship used to store, prepare and launch *TLAM*s, surface-to-air missiles, and rocket-thrown torpedoes.

EXECUTIVE SUMMARY

Since its inaugural combat use in Desert Storm, the Tomahawk Land Attack Missile (TLAM) has become the weapon of choice in strike warfare for U.S military forces. When either the NCA or regional Commander in Chief (CINC) authorizes the use of TLAMs against specified targets, *predesignation* determines which ship or submarine will fire its missiles in support of the attack. Predesignation is conducted in two distinct phases. In *Phase 1*, the Tomahawk Strike Coordinator (TSC) allocates TLAM target assignments, commonly referred to as *tasks*, to ships and submarines.

A heuristic for Phase 1 predesignation provides TSCs with quick and reasonable task-to-firing unit assignments to capture the following goals, in order of priority: (i) minimize any unmet tasking, (ii) avoid using units performing other duties in other areas, (iii) use as many missiles as possible from firing units that will soon leave a theatre of operations, (iv) level residual missile inventories among firing units that remain in a theatre of operations, (v) if desired, spread executable tasks among firing units, (vi) if desired, spread redundant tasks among firing units, (vii) use the least capable missile to execute a task, and (viii) preserve residual firing capability.

Our model also includes the following military-oriented features: (i) allow the TSC to choose whether to spread tasks among or restrict tasks to firing units on a per-target basis; (ii) allow allocation of special redundant tasks; (iii) accommodate submarines; and (iv) allow manual prioritization of the targets. This heuristic draws upon and improves a previous one that LT Bertram Hodge published in a Naval Postgraduate School thesis. Now, we ensure that a solution cannot be trivially improved. For a scenario with 104 tasks and 7 firing units, the heuristic delivers a plan in 7 seconds.

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I. INTRODUCTION

A. BACKGROUND

Since its inaugural combat use in Desert Storm, the Tomahawk Land Attack Missile (TLAM) has become the weapon of choice in strike warfare for U.S military forces. Because of its lethality, accuracy, and range, this weapon has provided the National Command Authority (NCA) with the ability to respond with force to crises without committing troops or necessitating a large military build-up.

When either the NCA or regional Commander in Chief (CINC) authorizes the use of TLAMs against specified targets, *predesignation* determines which ship or submarine will fire its missiles in support of the attack. Predesignation is conducted in two distinct phases. In *Phase 1*, the Tomahawk Strike Coordinator (TSC) allocates TLAM target assignments to ships and submarines; individual ships and submarines that receive these assignments are designated *firing units*. An assignment is referred to as a *task* and is characterized by: (i) a *mission*, i.e., a unique over-land flight path from the missile's point of launch to the target site; and (ii) a *time period*, i.e., an allowable interval of clock time during which the TLAM must be fired to complete the mission [Hodge, 1999]. During *Phase 2*, tasks are allocated to specific TLAMs onboard individual firing units based on additional considerations not accounted for in Phase 1. This thesis addresses only Phase 1 predesignation. [Fennemore, 1999]

Designating firing units and allocating tasks to them forces the Battle Group Commander to decide how to use and simultaneously defend his assets; these decisions can compromise existing capabilities and operations. Traditional Navy duties, such as ocean surveillance, contact identification, and maritime interdiction, require considerable

resources in a Carrier Battle Group (CVBG); TLAM tasks add additional strain on these resources. The United States Navy must carry out its traditional duties as well as the orders of the NCA and CINCs.

Currently, a TLAM is designed to attack a stationary, highly visible target, such as a bridge or a building; a TLAM attack on such a target requires hours to plan and execute. In the future, a TLAM must be able to attack a mobile target, such as a surface-to-air missile launcher or a radar site; such a task must be completed within minutes. An automatic predesignation procedure would enable tasks to be assigned quickly, efficiently, and in a reproducible fashion.

B. MISSILE OVERVIEW

Fired from ships or submarines, the Tomahawk Land Attack Missile is a subsonic, turbojet-powered weapon capable of low altitude penetration of hostile airspace. Prior to launch, each TLAM must be *aligned,* by energizing the missile's navigational equipment, activating the onboard computers, and loading mission software. After launch, the missile flies a pre-planned route, updates its position throughout the flight, and then detonates on the target.

A Tomahawk may be classified by its software and engine combination, i.e., by its *block*, and by its warhead. The missile's block and warhead combination is referred to as the TLAM *variant.* A Block II missile is the standard TLAM and navigates using *TERCOM*, which compares the over-flown terrain to a stored map in the missile's computer memory. A Block III missile has greater range than the earlier Block II missile and navigates using the Global Positioning System (GPS), which is more accurate than the older, TERCOM method. The future Block IV missile, nominally the *Tactical*

Tomahawk, will navigate via GPS and incorporate improvements over the Block III missile: the Block IV missile will be able to be re-programmed during flight, will fly farther, and will be able to attack a mobile target.

The other TLAM characteristic is its warhead. A unitary warhead possesses one large explosive and is designated "C", while a submunition warhead is designated "DI" or "DII". A "DI" warhead dispenses high explosive bomblets; a "DII" warhead scatters a unique, tailored submunition. A "DII" warhead receives an additional classification, referred to as a *kit number*, which differs depending on its specific target.

Rapid reprogramming downloads a different mission into a TLAM without re-performing the entire alignment procedure [Chief of Naval Operations, 1996]. A ship has this capability when it uses Block III or Block IV missiles; all TLAMs fired from submarines can be rapidly reprogrammed.

A more advanced TLAM may be substituted for a mission requiring a less capable missile if the guidance methods match. Table 1 summarizes allowable substitutions. A Block IV missile substitution for a Block III mission will not always be acceptable. A Block III missile navigates using GPS or TERCOM, depending on how the mission is constructed. A Block IV missile uses GPS. Even though block requirements are flexible, warhead stipulations are not because target destruction is warhead-specific. The desired effect requested by the NCA or CINC determines which type of missile is used.

		Acceptable Missile Blocks		
Required Block	**Guidance**	**II**	**III**	**IV**
II	**TERCOM**	Yes	Yes	No
III	**GPS or TERCOM**	No	Yes	Yes - GPS Only
IV	**GPS**	No	No	Yes

Table 1. Allowable Block Substitutions

A more advanced TLAM may be substituted for a mission requiring a less capable missile if the guidance methods match. A Block IV missile substitution for a Block III mission will not always be acceptable. A Block III missile navigates using GPS or TERCOM, depending on how the mission is constructed. A Block IV missile uses GPS. Even though block requirements are flexible, warhead stipulations are not because target destruction is warhead-specific.

C. THE VERTICAL LAUNCHING SYSTEM

The MK 41 Vertical Launching System (VLS) is used on U.S. Navy Ticonderoga class cruisers and Spruance and Arleigh Burke class destroyers. The basic unit of the system is a module, which is installed below deck to store, prepare, and launch weapons. TLAMs cannot be reloaded in the VLS while the ship is at sea. Figure 1 illustrates the two types of VLS modules available – the standard and the crane module. The standard 8-cell module is divided into *half-modules* consisting of Cells 1-4 and 5-8. A crane occupies Cells 6-8 in a crane module. In the crane module, Cell 5 is considered its own half-module. A module provides power and computer connections for each weapon to be fired from the cell.

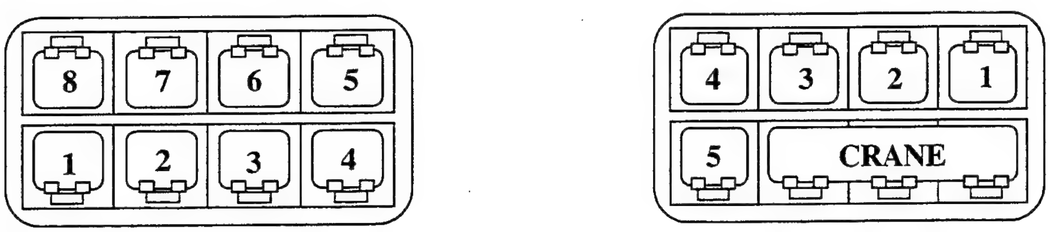

Figure 1. Typical VLS Modules

The basic unit of the system is a module, which is installed below deck to store, prepare, and launch weapons. Each module is subdivided into half-modules, consisting of Cells 1-4 and 5-8. A crane occupies Cells 6-8 in a crane module. In the crane module, Cell 5 is considered its own half-module. A module provides power and computer connections for each weapon to be fired from the cell.

VLS modules are grouped together to form launchers; the U.S. Navy uses an 8-module, full-size launcher and a 4-module, half-size launcher. Both launcher sizes have one crane module per launcher and are illustrated in Figure 2. The full-size launcher provides 61 cells for the loadout of ordnance while the half-size launcher provides 29 cells. A Ticonderoga class cruiser has two full-size launchers, a Spruance class destroyer has one full-size launcher, and an Arleigh Burke class destroyer has a full-size launcher and a half-size launcher. Launcher (forward or aft), module number, and cell number delineate weapon locations. For example, "Forward, 3, 2" refers to the forward launcher, Module 3, Cell 2.

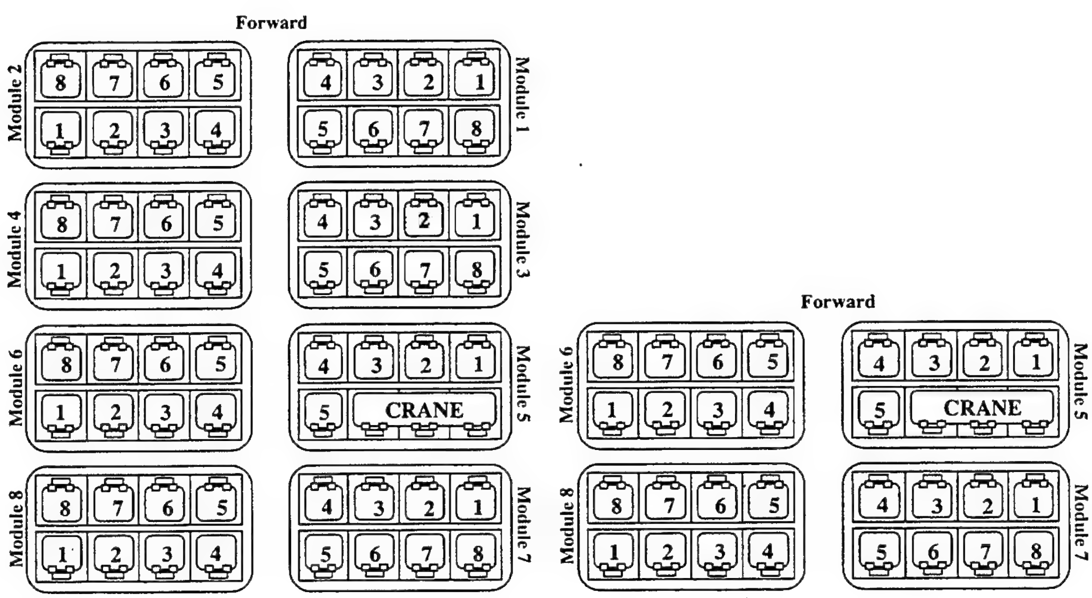

Figure 2. Full-size (left) and Half-size (right) VLS Launchers

A Ticonderoga class cruiser has two full-size launchers, a Spruance class destroyer has one full-size launcher, and an Arleigh Burke class destroyer has a full-size launcher and a half-size launcher. The "Forward" label indicates launcher orientation onboard the ship. Launcher (forward or aft), module number, and cell number delineate weapon locations. For example, "Forward, 3, 2" refers to the shaded forward launcher, Module 3, Cell 2.

Salvo size refers to the number of TLAMs that a firing unit can align and fire during one time period. The number of TLAMs fired from a ship's VLS launcher is restricted by a half-module power constraint; only one TLAM can be aligned at once per half-module. Tasks requiring TLAMs that must be aligned at the same time are said to *conflict*. Due to power constraints, a full-size launcher can align a maximum of 16 TLAMs at a time while a half-size launcher can align a maximum of 8 missiles. To eliminate the associated effect of *missile masking*, a task that requires a rare TLAM variant should be assigned before a task requiring a more common missile variant. Table 2 summarizes various attributes of and salvo size capabilities for each ship class.

Ship Class	Forward Launcher	Aft Launcher	Total Number of Cells	Number of Half-modules	Maximum Salvo Size
Ticonderoga	Full	Full	122	32	32
Spruance	Full	None	61	16	16
Arleigh Burke	Half	Full	90	24	24

Table 2. Comparison of TLAM Capabilities Based on Ship Class

The number of TLAMs fired from a ship's VLS launcher are restricted by a half-module power constraint; only one TLAM can be aligned at once per half-module. Due to power constraints, a full-size launcher can prepare a maximum of 16 TLAMs at a time while a half-size launcher can prepare a maximum of 8 missiles.

D. SUBMARINE LAUNCHING SYSTEMS

A submarine can fire TLAMs from torpedo tubes. In addition, a Los Angeles class submarine with a hull number of 719 or higher has a Capsule Launching System (CLS) that provides 12 capsules exclusively for firing TLAMs; if necessary, these capsules can simultaneously align all 12 missiles for launch. The CLS on a submarine is analogous to the surface ship VLS, and, similarly, cannot be reloaded at sea, *but is not restricted by the same half-module power constraint.*

A torpedo tube fires torpedoes or launches TLAMs; a TLAM is loaded into the torpedo tube, aligned, and fired like a torpedo. Because the torpedo tubes can be reloaded, the total quantity and variety of TLAMs launched from the torpedo tube depends on the submarine's internal weapon capacity. The TSC selects the missiles located in the torpedo room that best meet the task requirements. A submarine's torpedo tubes are analogous to a ship's VLS, and, like the CLS, the torpedo tube has no half-module power constraint.

Submarine salvo size refers to the number of TLAMs that can simultaneously be prepared and fired from the torpedo tubes and/or CLS. Table 3 summarizes the capabilities of each submarine class.

Submarine Class	Installed CLS	Number of CLS capsules	Number of Torpedo Tubes	Internal Weapon Capacity	Maximum Salvo Size
Los Angeles 688-718	No	0	4	At least 20	4
Los Angeles 719-773	Yes	12	4	At least 20	16
Seawolf	No	0	8	At least 40	8

Table 3. Comparison of TLAM Capabilities Based on Submarine Class

A submarine can fire TLAMs from torpedo tubes. In addition, a Los Angeles class submarine with a hull number of 719 or higher has a Capsule Launching System (CLS) that provides 12 capsules exclusively for firing TLAMs; if necessary, these capsules can simultaneously align all 12 missiles for launch.

E. SHIP OPERATIONAL CAPABILITIES AND LIMITATIONS

A ship carries more missiles and sustains larger salvo sizes than a submarine. A ship communicates better than a submarine with the Tomahawk Strike Coordinator (TSC) and other firing units in order to coordinate and update the status of a TLAM task. By monitoring the missile with its radars and data links, a ship provides the TSC with

vital information; the TSC can quickly re-assign firing units to complete a task for which a missile has failed. A ship maintains the ability to defend itself while firing TLAMs and is simultaneously able to conduct other operations, such as hunting submarines or engaging enemy aircraft.

Despite its advantages, a ship does have drawbacks. Its ability to conduct multiple operations simultaneously can hinder its capacity to complete TLAM tasks. For example, a ship engaged in maritime interdiction may be forced into a geographical position that diminishes its ability to fire a TLAM. In order to effectively coordinate TLAM tasks between the TSC and other firing units, a ship engaged in TLAM operations incurs speed and mobility restrictions. This limits a ship's ability to use the expanse of the ocean to hide, making the ship more susceptible to detection and attack. The scope of Battle Group operations and the strength of the enemy determine how relevant these limitations are. Despite these drawbacks, ships are still considered the backbone of TLAM employment.

F. SUBMARINE OPERATIONAL CAPABILITIES AND LIMITATIONS

A submarine approaches its target with stealth, fires its weapons undetected, and escapes into the vastness of the ocean. During TLAM operations, a submarine is usually confined to a smaller area than normal. It incurs speed and depth restrictions when firing TLAMs, and in order to communicate must travel close to the ocean's surface with its antennas raised above the water. An observed TLAM fired from a CLS or torpedo tube reveals the submarine's location.

Even with advanced communications gear, a submarine has more trouble maintaining continuous radio contact with the TSC and other firing units than a ship.

Therefore, short-notice orders from the TSC to a submarine may not be received. Also, a submarine cannot track missiles during flight.

A torpedo tube-launched TLAM occupies the tube during missile alignment. If TLAMs occupy all of the torpedo tubes, the submarine forfeits its attack abilities against enemy ships or submarines. Depending on the situation, the submarine Commanding Officer may restrict the number of torpedo tubes he will load with TLAMs.

Nonetheless, submarines play an important role in TLAM operations. Until they fire, they are very stealthy, and, if no immediate threat to them is present, their weaknesses are less relevant. Because of political considerations and lack of official and generally-accepted guidance, we ignore these relative capabilities and limitations of ships and submarines in our predesignation heuristic. The Tomahawk Strike Coordinator should carefully consider the differences of these two firing platforms and promote or limit their use, as necessary.

G. PREDESIGNATION PHASE 1

A *launch area* is a large geographic region from which the TLAM must be fired in order to reach the target. Examples of launch areas are the Northern Arabian Gulf, the Eastern Mediterranean Sea, and the Red Sea. A large group of ships, such as a Carrier Battle Group (CVBG), is associated with a launch area. For purposes of predesignation herein, a firing unit cannot relocate from one launch area to another. Depending on the target and the tasks associated with it, the TSC may use multiple launch areas with multiple groups of ships to increase the available pool of potential firing units.

A *launch basket* for executing a given task is designated based on the range of the missile and the distance to the target from a specific launch area; it indicates a region

within the launch area from which a firing unit may launch its TLAMs in order to complete a task. A firing unit located within or able to relocate to a launch basket is considered *geo-feasible* [Kirk, 1999].

Each TLAM target is identified by a unique, ten-digit alphanumeric code termed a *Basic Encyclopedia Number* (BEN). Designated by two letters, *aimpoints* are used to refine TLAM impact points by specifying a position on the target. Each BEN may have multiple missions and multiple aimpoints assigned to it. Figure 3 depicts the BEN, mission, and aimpoint relationship for the Shahiyat Liquid Engine Test Facility in Iraq after it was destroyed during Operation Desert Fox in December, 1998 [Federation of American Scientists]. The entire facility is assigned one BEN; the arrows indicate aimpoints where TLAMs impacted the target. This facility required two missions, each with its own aimpoint.

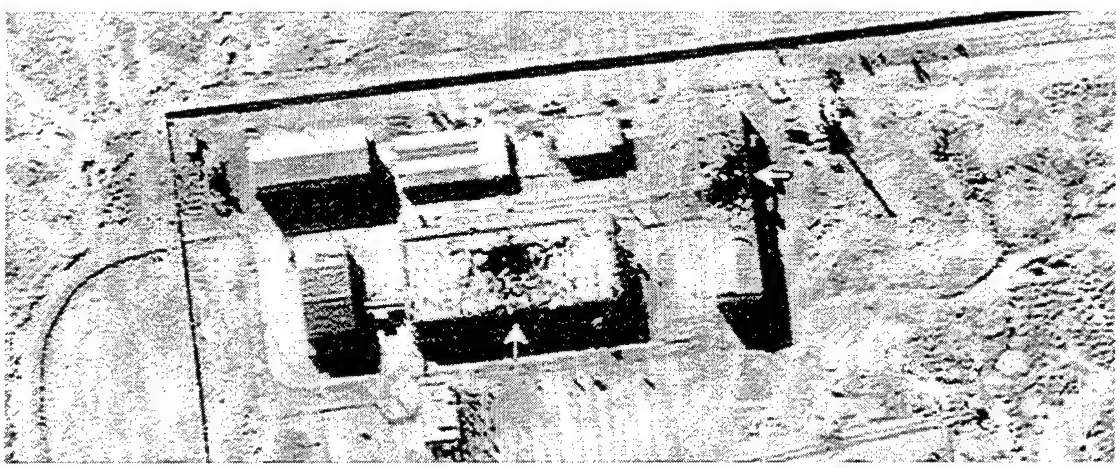

Figure 3. TLAM Target and Aimpoints

Each TLAM target is identified by a unique, ten-digit alphanumeric code termed a *Basic Encyclopedia Number* (BEN). Designated by two letters, aimpoints are used to refine TLAM impact points by specifying a position on the target. This particular example illustrates the BEN, mission, and aimpoint relationship for Shahiyat Liquid Engine Test Facility in Iraq after it was destroyed during Operation Desert Fox in December, 1998 [Federation of American Scientists]. The entire facility is assigned one BEN and the arrows indicate aimpoints where TLAMs impacted the target. This facility required two missions, each with its own aimpoint.

The TSC may want to ensure simultaneous TLAM arrival time for all tasks associated with a particular target on the target list. In this case, the number of firing units executing these tasks should be kept to a minimum to reduce coordinating communication among firing units and TLAM arrival time variation. A target with a limit on the number of firing units to which its corresponding tasks may be assigned is called a *restricted target*; the *target type* refers to whether a target is restricted or not.

To begin Phase 1 predesignation, the NCA or CINC provides the TSC the following information: a prioritized list of targets, a list of aimpoints at the target, the desirable and feasible missile types, the number of missiles per aimpoint, arrival time at the aimpoint, and information as to additional missions required to ensure success for each aimpoint (i.e., aimpoint redundancy).

From these inputs, the TSC selects a set of pre-planned missions that meet the NCA or CINC criteria. A mission defines the target, aimpoints, warhead, block, and launch area. An 11-digit number called a Mission Identification Number (MID) identifies each mission.

Feasible missile variants for the mission are listed on the *missile mission matching* (M^3) list. Every mission has an M^3 list that indicates the relative desirability of all capable missile variants. Using the NCA or CINC inputs as a guide, the TSC selects the quantity and variants of TLAMs required to complete each mission. A task has an earliest and latest time to launch (ETL and LTL, respectively) derived from the required arrival time at the aimpoint and missile flight parameters. The time span during which a TLAM could occupy a half-module, CLS capsule, or torpedo tube and still be fired in order to complete each task is based on ETL, LTL, and TLAM alignment time.

A task is identified by its BEN and MID and may be composed of up to three *task parts*: primary, ready-spare and/or backup. These tasks are assigned to missiles onboard firing units under a set of Tomahawk doctrinal constraints imposed by the Navy. A primary task part (or *primary missile*) is designated to be launched at a target; a ready-spare and/or backup task part (i.e., *ready-spare* or *backup missile*, respectively) is only launched in the case of primary failure. A ready-spare task part is assigned to the same firing unit as the primary; a backup task part is assigned to a different unit. Multiple missiles may be required for each task part. For example, assume a task has a primary task part that requires three missiles and a ready-spare task part that requires only one. In order for the task to be properly allocated, both task parts and all four missiles must be allocated to the same firing unit. For calculation purposes, we assume that all missiles associated with primary task parts are fired, and those associated with ready-spare and backup task parts are not.

Doctrinal constraints apply to targets as well. If a task is directed at a non-restricted target and possesses primary, ready-spare, and/or backup task parts, all the missiles associated with that task may be spread among the geo-feasible firing units, provided that the assignments follow the convention for primary, ready-spare, and backup task part allocation. Restricted targets have their tasks and associated task parts allocated to as few firing units as possible.

The *weighted salvo size* (as opposed to the *salvo size*) for each firing unit is calculated to provide an indication of the number *and type* of TLAMs a firing unit can align and fire during one time period. For a surface ship, the weighted salvo size is the sum of the product of the relative weight associated with a missile's capability and the

most capable missile in the half-module. For submarines, rather than considering the most capable missile in the half-module, we consider the missiles located in the CLS capsules along with the n most capable missiles that remain in the torpedo room, where n represents the number of torpedo tubes that are being used to launch TLAMs.

Due to software that controls the TLAMs during alignment, each firing unit has a limited number of TLAM task parts that can simultaneously be assigned to it during a single time period; this number is static for each ship and submarine class and is referred to as the *planning size*. *Planning capacity* refers to the greatest number of TLAM task parts a firing unit can be allocated in a single time period.

A special type of task, referred to as a *ghost task*, enables one missile to provide simultaneous redundancy for multiple tasks and multiple task parts. A ghost task is fired when ordered by the TSC and may be categorized as a combination of ready-spare and/or backup task parts. If a ghost task provides redundancy for a ready-spare task part, the ghost task must be assigned in the same manner as the primary and ready-spare task part combination; if a ghost task provides redundancy for a backup task part, it is assigned in the same manner as the primary and backup task part combination. Even though each ghost task part uses only one TLAM, each task part assignment reduces the firing unit's available planning size. For calculation purposes, we assume that ghost tasks are not fired.

Multiple targets are grouped together to form a *target list.* A *strike* entails allocating TLAMs to the maximum possible number of targets on the target list, and may extend over multiple time periods.

H. PAST WORK

Naval Surface Warfare Center Dahlgren Division (NSWCDD) has supported Naval Postgraduate School missile predesignation research. NSWCDD has developed a mixed-integer program that models Phase 2 predesignation onboard individual ships and submarines [Naval Surface Warfare Center Dahlgren Division 1997, 1999]. Three previous Naval Postgraduate School theses address various Tomahawk selection problems. LT Scott Kuykendall's thesis "Optimizing Selection of Tomahawk Cruise Missiles" presents a mixed-integer formulation capable of performing Phase 1 or Phase 2 predesignation [Kuykendall 1998]. Kuykendall's program demonstrates the use of a mixed-integer program but does not address the entire scope of predesignation; for example, his work does not include all goals a TSC may want to consider. LT Brian Kirk develops an optimization model for completing Phase 1 for surface ships using multiple objective functions to capture a variety of goals. While these goals do not represent any official guidance, they have been informally reviewed by Tactical Training Group Atlantic and found acceptable [Williams, 1998]. These goals, or *objectives*, are summarized below, in descending order of priority, where a goal with a higher priority is considered infinitely more important than a goal of a lesser priority [Kirk, 1999]:

- **Objective 1**: Meet all assigned tasking.
- **Objective 2**: Minimize the number of firing units engaged in other duties or the number of firing units that must relocate to fire TLAMs. An *employment penalty* is assigned when a firing unit that is critical to the Battle Group's maritime operations is used for TLAM tasking. A *geographic penalty* is assigned to a firing unit that must relocate to a launch basket.

- **Objective 3**: Use as many missiles as possible from firing units designated to exhaust their TLAM inventories. These firing units are labeled *expend* firing units.
- **Objective 4**: Distribute missile assignments as much as possible among firing units not designated to expend their TLAM inventories. These firing units are labeled *spread* firing units. Equal residual TLAM inventory among firing units decreases the probability of failure to meet future target list requirements due to catastrophic loss (e.g., the destruction of a firing unit), equipment failure (e.g., a VLS malfunction), or inability to accomplish a task due to the unfavorable location of a firing unit.
- **Objective 5**: Spread primary task parts to as many firing units as possible to prevent single points of failure when attempting to fire primary task parts within a launch area. Kirk uses a binary toggle to activate this option for all firing units within a launch area.
- **Objective 6**: Spread backup task parts to as many firing units as possible to prevent single points of failure when attempting to fire backup task parts. Kirk uses a binary toggle to activate this option for all firing units within a launch area.
- **Objective 7**: Use the least capable missile possible from the M^3 list.
- **Objective 8**: Maximize weighted salvo size per strike.

Because each hierarchical objective is considered infinitely more important than the following one, a superior solution is realized once a task-to-firing unit allocation yields an objective value that is better in a higher-ranking objective, regardless of the values of the lower-priority objectives.

Kirk investigates three solution techniques. First, he implements an integer program with a single weighted objective function, but this method does not produce sensible answers for scenarios with realistically large task sets, and solution times are excessive. Next, he implements a multiple-objective integer program using Hierarchical Restriction (HR). Although he achieves solutions of acceptable quality, solution times are too long for the method to be operationally useful. Finally, he implements a Heuristic Hierarchical Restriction (HHR) method on the multiple-objective integer program. This method also achieves solutions of acceptable quality, and although solution times are significantly faster than those obtained with either of the two other methods, the solution times are still too slow for HHR to be used in an operational setting. The long solution times of all three mixed-integer programming approaches highlight a need for a purely heuristic approach. The near-optimal solutions Kirk obtains with HR provide a means to objectively assess the quality of heuristic solutions [Kirk 1999].

LT Bertram Hodge introduces a heuristic mimicking Kirk's solutions. LT Hodge's thesis "A Heuristic for Land-Attack Predesignation" uses a greedy algorithm first to select firing units, then to make task-to-cell assignments based on a single pass of a prioritized task list. Hodge evaluates his heuristic with respect to Kirk's near-optimal solutions. His heuristic produces solutions of reasonable quality for most objectives; however, his heuristic produces solutions about 15% worse, on average, than HR for the

objective of allocating primary task parts to ships designated to expend their TLAM inventories; his heuristic produces solutions about 50% worse, on average, than HR for the objective of leveling the residual distribution of missiles among the ships designated for conserving their TLAM inventories [Hodge 1999].

The Hodge heuristic produces task-to-firing unit allocations quickly enough for operational use; the relative speed of the heuristic becomes more pronounced as the size of the target list increases.

II. MODELING APPROACHES

A. PROBLEM DEFINITION

Our heuristic enhancements include military-oriented features not considered by Hodge: (i) we allow the TSC to spread tasks among or restrict tasks to firing units on a per-target basis; (ii) we ensure that the number of ghost task parts assigned does not exceed the planning size; (iii) we accommodate submarines; and (iv) we allow the TSC to manually prioritize all or part of the target list.

If the TSC wishes to ensure simultaneous TLAM arrival time for all tasks associated with a particular, i.e., restricted, target on the target list, the tasks associated with this restricted target must be allocated to as few firing units as possible.

A ghost task uses planning capacity that could be dedicated to other (non-ghost) tasks. A ghost task is most efficiently assigned based on a firing unit's *excess planning capacity*, which is obtained for a specific time period by subtracting a firing unit's salvo size from that firing unit's planning size. A firing unit with a large excess planning capacity is less limited for a ghost task assignment than a firing unit with a smaller excess planning capacity because the former category of firing units can accept a greater number of task allocations, provided some tasks have non-overlapping preparation and launch times.

Our heuristic considers submarines, the number of available torpedo tubes, and the torpedo room and CLS capacity of each.

The TSC may have a set of tasks that must be assigned before any others. We invite the TSC to manually assign a priority to each task based on the importance that a

target be struck in the designated time period, thereby over-riding other task assignment considerations.

We want to maximize TLAMs launched from expend firing units, so we assign a firing unit designated to expend its TLAM inventory as many primary task parts as possible, and as few ready-spare task parts, backup task parts, or ghost tasks, as possible. We assume, realistically, that primary task parts are executed and that ready-spare and backup task parts, as well as ghost tasks, are not.

We want to equalize TLAM inventories among firing units, so we allocate primary missiles to spread firing units with the highest inventories, and redundant missiles to spread firing units with the lowest inventories.

It is important that the heuristic produce a solution that a human operator cannot trivially improve. We ensure that a solution cannot be improved by any one-complement interchange of task-to-missile assignments.

B. ALGORITHM ASSUMPTIONS, DEFINITIONS, DATA, AND MODEL PRESENTATION

We state terms and assumptions to describe task composition and assignment. Most of these follow the work of Kirk and Hodge.

This model addresses only *Phase 1* predesignation. Even though task parts are allocated to the specific cell, capsule, or torpedo tube to ensure that task-to-firing unit assignments are feasible, the model does not consider *Phase 2* details, such as the regularly scheduled maintenance inspection date of a missile. Assigning task parts to a specific cell, capsule, or torpedo tube lends sufficient fidelity to ensure feasible task-to-firing unit assignments. [Hodge 1999]

We assume that ready-spare and backup task parts and ghost tasks have the same M^3 list as the primary task part. Additionally, we assign *task part points* to each task part to quantify the type of task parts associated with each task (and, therefore, the relative difficulty of assigning the task). Specifically, we allocate a primary task part 5 points, a ready-spare task part 4 points, a backup task part 3 points, and a ghost task 2 points. *Task points* are the sum of these.

All tasks sharing the same BEN must be allocated to ships and submarines within the same launch area. A ship or submarine may be assigned a task if it is geo-feasible and if it has a capable half-module, capsule, or torpedo tube. A particular ship or submarine is considered geo-feasible for an individual target if that ship or submarine is geo-feasible for *all* the tasks directed at that target. A half-module is considered capable of receiving an assignment if it has a capable cell and if no other previously-assigned task part conflicts with the task part requiring assignment. A cell is considered capable if it contains a missile that is listed on the task's M^3 list and if no other task part is assigned to that cell. A CLS capsule is considered capable if it contains a missile that is listed on the task's M^3 list and if no other task part is assigned to that capsule. A torpedo tube is considered capable if the torpedo room contains a TLAM on the task's M^3 list, and we can expect that TLAM to be loaded into an empty torpedo tube and aligned in time.

Among all the tasks directed at an individual target during a strike, the target's *restricted M^3 list* is the smallest M^3 list among all those associated with a given target. This list gives some indication of the relative difficulty of assigning the tasks associated with a given target: consider that the number of missiles that can be used to accommodate a task is roughly proportional to the size of the M^3 list, and that these

missiles are fairly evenly distributed among the half-modules. These assumptions are reasonably accurate based on standard ship and submarine loadouts. In addition, we assign each target a *primary missile-per-target ratio*, which is the ratio of the number of primary missiles to the total number of missiles (including redundancies) required by all the tasks directed at that target. The primary missile-per-target ratio indicates the proportion of redundancy for an individual target. Firing units that are designated expend or have large quantities of missiles should be assigned targets with a high primary missile-per-target ratio.

Kirk associates two types of penalties with each ship: a geographic penalty and an employment penalty. We extend this analogously to submarines. The penalties are expressed in the same arbitrary units and indicate the relative desire to use a ship or submarine as a firing unit. If used in a strike, the firing unit's *total penalty-per-firing unit* is the sum of its geographic penalty and its employment penalty. A *penalty firing unit* is a firing unit that incurs either a geographic and/or an employment penalty for its use.

Hodge defines a parameter $\boldsymbol{P}$ for each ship as its total penalty-per-firing unit divided by the number of capable half-modules onboard. The *weighted salvo size* divided by $\boldsymbol{P}$ yields the value $\boldsymbol{R}$, the *firing unit-TLAM-penalty ratio*, and a higher firing unit-TLAM-penalty ratio indicates that a ship is a preferable choice for task assignment among ships that incur a penalty for their use.

In Hodge's version of the heuristic, all tasks are assigned to ships without penalties, if possible. If a ship with a penalty is required to eliminate any unassigned tasks, Hodge considers assigning tasks to a single ship with the highest firing unit-TLAM-penalty ratio. If the addition of this ship eliminates all unassigned tasks, then no

other ships are considered. However, if the ship initially chosen does not eliminate all of the unassigned tasks, the remaining penalty ships are individually considered in decreasing order of their firing unit-TLAM-penalty ratios. If no single ship, in addition to the ships without penalties, can fully meet the tasking, all pairs of penalty ships are considered, in decreasing order of their combined firing unit-TLAM-penalty ratios. In general, in conjunction with the ships without penalties, all single, double, triple, etc., combinations of penalty firing units are considered in decreasing order of their combined firing unit-TLAM-penalty ratios until either all the tasks are allocated or all the ships have been considered. By considering (combinations of) ships in this fashion, Hodge hopes to efficiently arrive at the minimum number of ships that will cover all tasks with the least penalty.

In our version of the heuristic, we calculate the firing unit-TLAM-penalty ratio, ***R***, differently by eliminating the terms expressing the number of capable half-modules and the weighted salvo size. Our firing unit-TLAM-penalty ratio is obtained by dividing a firing unit's total penalty-per-firing unit by the total number of TLAMs currently onboard (see Figure 4). Eliminating the number of capable half-modules *may* result in a more efficient selection of firing units because: (i) more missiles, rather than a greater number of capable half-modules, *may* be a better indication of a firing unit's ability to accept tasks if the preparation and launch times of the majority of the tasks do not overlap; and (ii) a torpedo tube and a half-module are not equivalent because a torpedo tube can be reloaded at sea, whereas a cell on a surface ship cannot.

We eliminate weighted salvo size because: (i) its inclusion can promote the selection of a firing unit with fewer, highly capable missiles contained in a small number

of half-modules, capsules, or torpedo tubes over the selection of a firing unit with a greater number of slightly more capable missiles contained in a larger number of half-module, capsules, or torpedo tubes; and (ii) the selection of a firing unit with a large proportion of highly capable missiles increases the probability of allocating a task to an over-endowed missile.

$$R_{Hodge} \equiv \text{firing unit-TLAM-Penalty Ratio} = \frac{\text{weighted salvo size * capable half-modules}}{\text{total penalty-per-firing unit}}$$

$$R_{Arnold} \equiv \text{firing unit-TLAM-Penalty Ratio} = \frac{\text{total penalty-per-firing unit}}{\text{number of TLAMs onboard}}$$

Figure 4. Firing Unit-TLAM-Penalty Ratio Calculations

When selecting a firing unit with a positive firing unit-TLAM-penalty ratio, we select the firing unit with the *lowest* ratio first.

Inputs consist of requirement data and asset data.

Requirement data are composed of the targets, target data, and the specific task data for each target. Target data consist of the target's priority, the target's type, i.e., whether a target is restricted or not, and whether primary or backup task parts are desired to be spread among firing units. Task data include information regarding the number of tasks associated with each target, the M^3 list associated with each task, the number of task parts associated with each task, and the number of missiles required for each task part. The targets and the target-specific data constitute the *target list*. The tasks and task-specific data constitute an individual *task list* for each target.

Asset data describes firing units within each launch area, and the launch areas themselves. The set of firing units within each launch area is referred to as the *eligible units list* for targets that can be attacked from that launch area. All firing units within a launch area, whether they are designated expend, spread, or have a total penalty-per-firing unit greater than zero, are listed on the eligible units list. A firing unit with a total

penalty-per-firing unit greater than zero is *a priori* assigned to the "most reasonable" launch area (e.g., the launch area closest to the area in which the firing unit is currently positioned). The set of firing units on the eligible units list that actually receives TLAM assignments forms the *firing units list*. Initially, all firing units within a launch area that have a firing unit-TLAM-penalty ratio, $\boldsymbol{R}$, of zero compose the firing units list, which is a subset of the eligible units list.

The *launch area list* includes all the launch areas that contain geo-feasible ships and submarines that are candidates to receive task assignments. Each launch area has a *launch area BEN list* of the targets that can be attacked from that launch area. When a task is assigned to a firing unit, the associated target is also placed on that launch area's *launch area target list*, which indicates the targets that are to be attacked from that launch area. Figure 5 illustrates the asset data relationship.

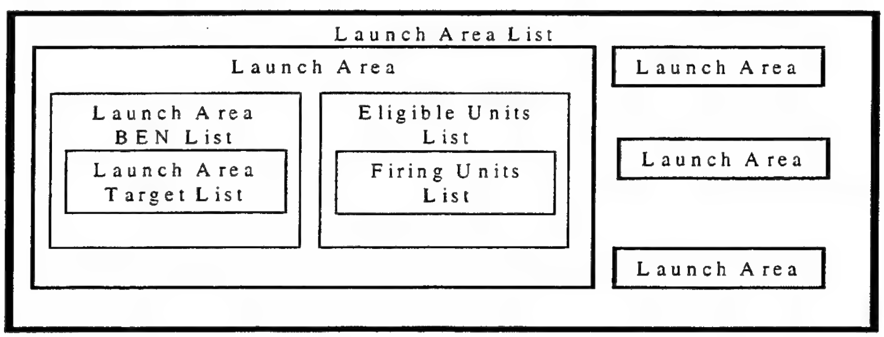

Figure 5. Asset Data Relationship

Asset data describes firing units within each launch area, and the launch areas themselves. The launch area list includes all the launch areas that contain geo-feasible ships and submarines that are candidates to receive task assignments. Each launch area has a launch area BEN list of the targets that can be attacked from that launch area. When a task is assigned to a firing unit, the associated target is also placed on that launch area's launch area target list, which indicates the targets that are to be attacked from that launch area. The set of firing units within each launch area is referred to as the eligible units list for targets that can be attacked from that launch area. The set of firing units on the eligible units list that actually receive TLAM assignments form the firing units list.

When ordering decreasingly *limited* launch areas, we sort increasing by targets on the launch area BEN list, and then increasing by number of firing units on the eligible units list. We allocate a target and its associated set of tasks to the single, most *limited* launch area among a set of launch areas that contains geo-feasible firing units; this allocation increases the probability of assigning all the targets on the target list by preserving the ability to assign targets to launch areas with more "capacity", if necessary. Table 4 shows a set of unordered launch areas. Because the least number of targets can

Launch Area	Attackable Targets	Number of Firing Units
Northern Arabian Gulf	10	7
Eastern Mediterranean	10	5
Northern Red Sea	5	10

Table 4. Unordered Launch Area List

The name of the launch area is in Column 1, the number of targets on the launch area BEN list is in Column 2, and the number of eligible firing units is in Column 3.

be attacked from the Northern Red Sea launch area, that launch area is considered the most limited and is placed first on the sorted launch area list. An equal number of targets can be attacked from the Northern Arabian Gulf and the Eastern Mediterranean launch areas. Because these launch areas are considered equally limited based on the number of targets on their respective launch area BEN lists, we prioritize them based on the number of firing units and their respective eligible units list. Because the Eastern Mediterranean launch area has fewer firing units, it is placed second on the launch area list and the Northern Arabian Gulf is placed last on the list. The ordered set of launch areas is illustrated in Table 5.

Sort Keys	Increasing 1	Increasing 2
Launch Area	**Assignable BENs**	**Number of Firing Units**
Northern Red Sea	5	10
Eastern Mediterranean	10	5
Northern Arabian Gulf	10	7

Table 5. Ordered Launch Area List

Because the least number of targets can be attacked from the Northern Red Sea launch area, that launch area is considered the most limited and is placed first on the sorted launch area list. An equal number of targets can be attacked from the Northern Arabian Gulf and the Eastern Mediterranean launch areas. Because these launch areas are considered equally limited based on the number of targets on their respective launch area BEN lists, we prioritize them based on the number of firing units and their respective eligible units list. Because the Eastern Mediterranean launch area has fewer firing units, it is placed second on the launch area list and the Northern Arabian Gulf is placed last on the list.

To mitigate the myopia of our single-pass heuristic, we employ two successive allocations with different target list sequencing. The algorithm uses the requirement and asset data to perform *conservative* and *aggressive allocation* of tasks to firing units. Conservative allocation seeks the best values for the two most important objectives: make a complete task-to-firing unit allocation while minimizing the use of firing units engaged in other activities or located in other areas. Aggressive allocation improves lesser-priority objectives at the risk of deteriorating the value of the first objective. Depending on the instance, aggressive allocation may produce superior solutions.

Conservative allocation assigns targets to launch areas. If any tasks associated with a target cannot be assigned to the current launch area, the next least limited launch area is then considered for that target assignment. If there are any targets that cannot be allocated to any launch area given the current firing units on the firing units list, the firing unit with the lowest firing unit-TLAM-penalty ratio is added to the first launch area on the launch area list (i.e., the most limited launch area), and *all* targets are reallocated. If targets still remain unallocated, we add the firing unit in the next least limited launch area with the lowest firing unit-TLAM-penalty ratio, and the targets are again reallocated. Firing units with non-zero firing unit-TLAM-penalty ratios are added one by one to launch areas in decreasing order of the launch area's limitations; after a single firing unit has been added to each launch area, the two firing units with the lowest combined firing unit-TLAM-penalty ratio are added to each launch area, etc. until all targets are assigned. Figure 6 provides a graphical description of how firing units with a non-zero firing unit-TLAM-penalty ratio are added to a launch area's firing units list.

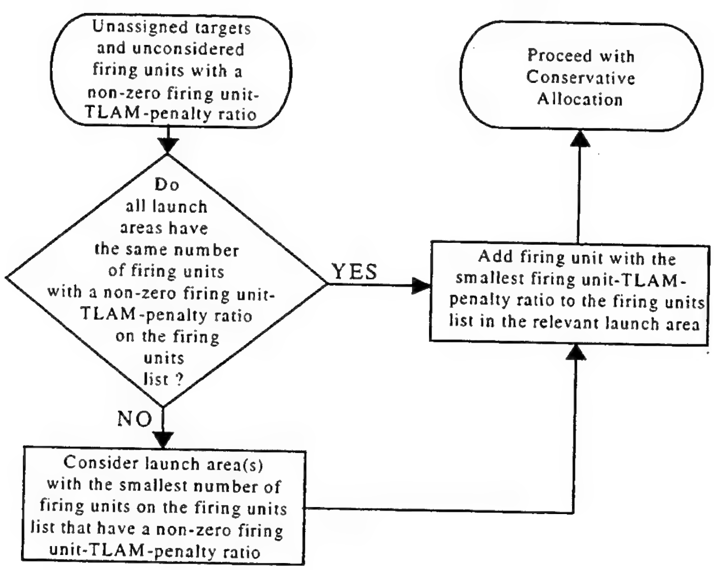

Figure 6. Addition of Firing Units with Non-Zero Firing Unit-TLAM-Penalty Ratios

If all firing units on the eligible units list have been considered, and unassigned task parts remain, all task parts associated with that task are marked as unassigned. Should unassigned tasks associated with a target remain, all tasks associated with that target are marked as unassigned only if the target is restricted.

The target list is sorted by seven keys: (i) decreasing target priority, (ii) increasing number of geo-feasible firing units for that target, (iii) restricted target type, then unrestricted target type, (iv) increasing number of half-modules, CLS capsules, and torpedo tubes capable of firing the tasks associated with the target, (v) increasing length of a target's restricted M^3 list, (vi) decreasing total number of task points associated with the tasks for that target, and (vii) decreasing number of conflicting targets. Table 6 shows an unsorted target list that is sorted in Table 7. Each target's corresponding task list is sorted, first descending by the number of task points, and then descending by number of missiles associated with each task.

BEN	Target Priority	Firing Units	Target Type	Capable Half-modules, Capsules, Tubes	Restricted M^3 List	Total Task Points	Conflicting Targets
3004005000	2	10	restricted	150	2	3	7
3004005100	2	10	unrestricted	150	1	6	7
3004005200	2	10	unrestricted	150	2	9	7
3004005300	2	10	unrestricted	150	1	12	7
3004005400	2	10	restricted	150	2	15	14
3004005500	2	5	restricted	75	1	3	14
3004005600	2	5	restricted	100	2	6	7
3004005700	2	5	unrestricted	75	1	9	14
3004005800	2	5	unrestricted	75	2	12	14
3004005900	2	10	unrestricted	150	1	6	14
3004006000	1	10	unrestricted	150	2	3	14
3004006100	1	10	restricted	150	1	6	7
3004006200	1	5	restricted	75	2	9	14
3004006300	1	5	unrestricted	75	1	12	7

Table 6. Unsorted Target List

The BEN for each target is in Column 1, the target's priority is in Column 2, the total number of capable firing units is in Column 3, the target type is in Column 4, the total number of capable half-modules, CLS capsules, and torpedo tubes among all the launch areas is in Column 5, the number of missiles on the restricted M^3 list is in Column 6, the number of task points for each target is in Column 7, and the number of conflicting targets is in Column 8.

Sort Keys	Decreasing 1	Increasing 2	Restricted, then Unrestricted 3	Increasing 4	Increasing 5	Decreasing 6	Decreasing 7
BEN	Target Priority	Firing Units	Target Type	Capable Half-modules, Capsules, Tubes	Restricted M^3 List	Total Task Points	Conflicting Targets
3004006200	1	5	restricted	75	2	9	14
3004006300	1	5	unrestricted	75	1	12	7
3004006100	1	10	restricted	150	1	6	7
3004006000	1	10	unrestricted	150	2	3	14
3004005500	2	5	restricted	75	1	3	14
3004005600	2	5	restricted	100	2	6	7
3004005700	2	5	unrestricted	75	1	9	14
3004005800	2	5	unrestricted	75	2	12	14
3004005400	2	10	restricted	150	2	15	14
3004005000	2	10	restricted	150	2	3	7
3004005200	2	10	unrestricted	150	2	9	7
3004005300	2	10	unrestricted	150	1	12	7
3004005900	2	10	unrestricted	150	1	6	14
3004005100	2	10	unrestricted	150	1	6	7

Table 7. Sorted Target List

The seven sort keys begin with target priority.

In conservative allocation, firing units are assigned tasks based on a *spread ship scoring* method and whether the firing units are designated expend or spread. By balancing the number of missiles onboard each firing unit with that unit's number of capable half-modules, capsules, and torpedo tubes, this method usually assigns all tasks while employing a low number of firing units engaged in other activities or located in other areas. In addition, spread ship scoring levels the TLAM inventories of the firing units remaining in the launch area. Prior to allocating each task, all of the ships and submarines on the firing units list receive a spread ship score. Spread ship scoring assigns two points to a firing unit for every half-module, CLS capsule, and torpedo tube that does not have a primary task part assigned to it, and it assigns one point for every cell, capsule, or torpedo tube that does not have an assigned primary task part

The advantage of spread ship scoring is best illustrated with an example from Hodge. Consider two firing units, Unit A and Unit B (Figure 7). Unit A, with four capable half-modules, has one block-III C TLAM per half-module. Unit B has three block-III C TLAMs in each of its two capable half-modules. Two conflicting tasks must be assigned. Task 1 has primary, ready-spare, and backup task parts each requiring one block-III C TLAM. Task 2 also requires block-III C TLAMs, but it has only a primary and backup task part, each requiring one missile. If the tasks are assigned based on the number of TLAMs onboard, Task 1's primary (T1 P) and ready-spare (T1 R) task parts will be assigned to Unit B, and the backup (T1 B) task part will be assigned to Unit A. Task 2 cannot be assigned because the neither the primary nor backup task part can be assigned to Unit B (Figure 8).

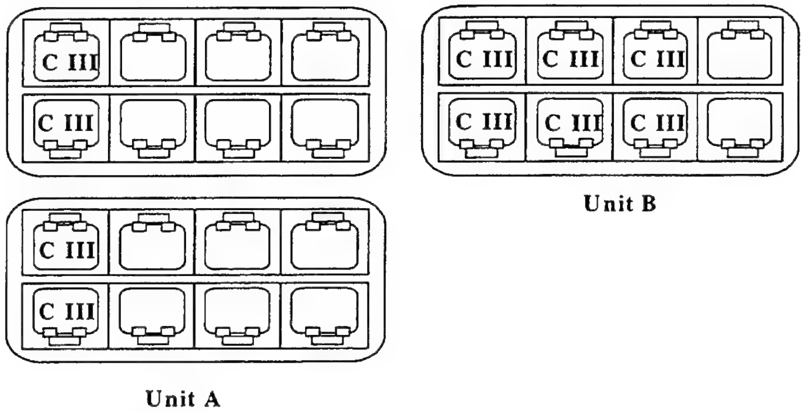

Figure 7. An Example Inviting Spread Ship Scoring

Consider two firing units, Unit A and Unit B. Unit A, with four capable half-modules, has one block-III C TLAM per half-module. Unit B has three block-III C TLAMs in each of its two capable half-modules. Two conflicting tasks must be assigned.

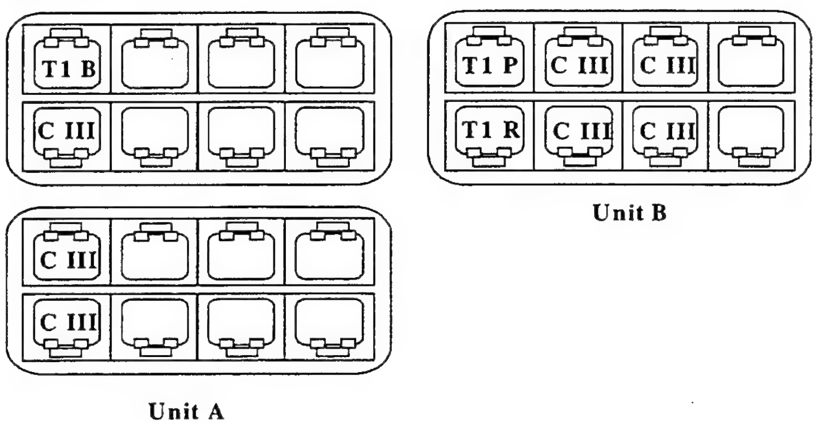

Figure 8. Task Part Assignment Using Number of TLAMs

Two conflicting tasks must be assigned. Task 1 has primary, ready-spare, and backup task parts each requiring one block-III C TLAM. Task 2 also requires block-III C TLAMs, but it has only a primary and backup task part, each requiring one missile. If the tasks are assigned based on the number of TLAMs onboard, Task 1's primary (T1 P) and ready-spare (T1 R) task parts will be assigned to Unit B, and the backup (T1 B) task part will be assigned to Unit A. Task 2 cannot be assigned because the neither the primary nor backup task part can be assigned to Unit B.

If spread ship scoring is used, Unit A receives a total of 12 points, two for every non-primary-assigned half-module and one point for every missile that is not assigned a primary task part. Unit B receives 10 points, two for every non-primary-assigned half-module and one point for every missile that is not assigned a primary task part. Task 1's primary (T1 P) and ready-spare (T1 R) task parts are assigned to Unit A first, and the backup task part (T1 B) is allocated to Unit B. After re-calculating the scores following the allocation of Task 1, Unit A has a spread ship score of 9 and Unit B still has a score of 10. Unit B is allocated Task 2's primary (T2 P) task part and Unit A is assigned the backup (T2 B) task part. Figure 9 illustrates how spread ship scoring allocates the two tasks.

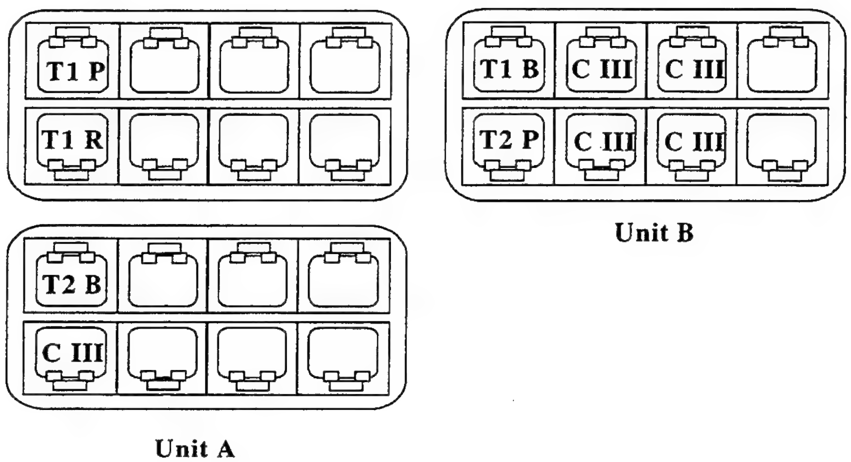

Figure 9. Task Part Assignment Using Spread Ship Scoring

If spread ship scoring is used, Unit A receives a total of 12 points, two for every non-primary-assigned half-module and one point for every missile that is not assigned a primary task part. Unit B receives 10 points, two for every non-primary-assigned half-module and one point for every missile that is not assigned a primary task part. Task 1's primary (T1 P) and ready-spare (T1 R) task parts are assigned to Unit A first, and the backup task part (T1 B) is allocated to Unit B. After re-calculating the scores following the allocation of Task 1, Unit A has a spread ship score of 9 and Unit B still has a score of 10. Unit B is allocated Task 2's primary (T2 P) task part and Unit A is assigned the backup (T2 B) task part.

Balancing the demands of Objective 3 and 4, i.e., maximizing the assignment of primary missiles to expend firing units and leveling the missile inventory of spread firing units, we must consider whether the firing unit is designated expend or spread, and the type of task parts that compose each task. Specifically, primary and ready-spare task part combinations (regardless of whether the task additionally possesses a backup task part and/or a ghost task) are assigned to the spread firing unit with the highest spread ship score. Backup task parts are assigned to the firing unit with the lowest spread ship score. This helps to maintain the inventory of firing units with a small number of missiles, because we assume that backup task parts are not fired. Ghost tasks are assigned to the spread firing unit with the lowest spread ship score that has excess planning capacity. If several firing units have the same spread ship score, the ghost task is assigned to the firing unit with the greatest excess planning capacity. If no spread firing unit can accept a primary and ready-spare task part combination, the expend firing unit with the highest spread ship score is considered to be assigned those task parts. Any corresponding backup task parts and ghost tasks are assigned to the expend firing unit with the lowest spread ship score.

If a task has only a primary task part, a primary and a backup task part, or a primary task part and a ghost task, the primary task part is assigned to the *expend* firing unit with the highest spread ship score. The corresponding backup task part is assigned to the spread firing unit with the lowest spread ship score. If there are no expend firing units or the task part cannot be assigned to the expend firing units, the spread firing unit with the highest spread ship score is considered for primary task part assignment, and the

spread firing unit with the lowest spread ship score is considered for backup task part and ghost task assignment.

We use a *half-module scoring method* to determine the placement of missiles associated with task parts in half-modules onboard a ship. This scoring method is an adaptation from Hodge. Each missile type on the task M^3 list that is in a half-module receives a number of points equal to its distance from the end of the M^3 list, e.g., the second missile on an M^3 list with 5 missile types receives a score of 4. Each half-module accumulates the sum of these points for its missiles. Each missile associated with each task part is assigned to the half-module with the highest accumulation. A least-capable missile in the highest-scoring half-module is assigned. For submarines, each missile associated with each task part is assigned to the CLS capsule with the least capable TLAM, or to the least capable TLAM in the torpedo room or a torpedo tube. Figure 10 depicts the conservative allocation.

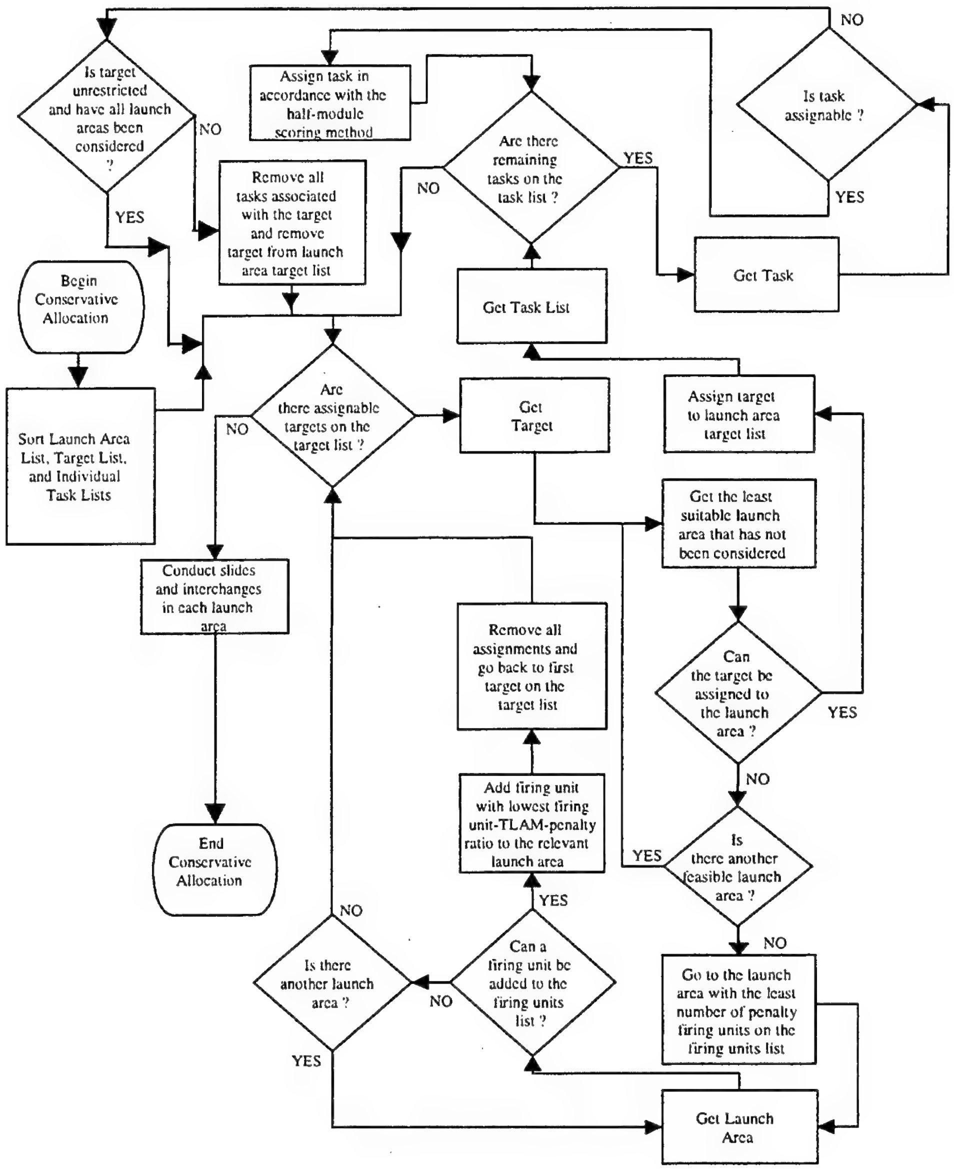

Figure 10. Conservative Allocation

This one-pass, myopic allocation depends upon the sequence of heuristically-sorted lists of launch areas, targets, and tasks. Limited backtracking occurs when an unassignable target is removed along with all its tasks. The last step employs one-complement slides and interchanges to achieve local optimality.

We try to improve conservative allocation with aggressive allocation. Aggressive allocation inherits and reuses the launch area assembly of targets and the firing units from conservative allocation. Aggressive allocation ignores: (i) target priority, (ii) the number of geo-feasible firing units, (iii) target type, (iv) the number of capable half-modules, capsules, and torpedo tubes, and (v) the number of conflicting targets.

Aggressive allocation sorts the targets on the launch area target list by three keys: (i) ascending by length of target restricted M^3 list, (ii) descending by target primary missile-per-target ratio, and (iii) descending by number of missiles associated with each target. By considering targets with a greater number of primary missiles first, we directly allocate primary missiles to both expend and spread firing units, thereby improving Objectives 3 through 8 (but not Objective 6). Finally, we consider the targets in decreasing order of the number of missiles associated with the target, because targets with a greater associated number of missiles are more difficult to allocate. An unsorted launch area target list is given in Table 8, and is sorted ascending by M^3 cardinality, descending by primary missile-per-target ratio, and descending by total number of missiles in Table 9.

BEN	Restricted M^3 List	Primary Missile-per-Target Ratio	Total Missiles
3004005000	2	1	1
3004005100	1	1	2
3004005200	2	1	3
3004005300	1	1	4
3004005400	2	0.5	2
3004005500	1	0.5	4
3004005600	2	0.5	6
3004005700	1	0.5	8
3004005800	2	0.5	10
3004005900	1	0.5	12
3004006000	2	0.3	3
3004006100	1	0.3	6
3004006200	2	0.3	9
3004006300	1	0.3	12

Table 8. Unsorted Launch Area Target List

Each target is represented by its BEN in Column 1, the number of TLAMs on the most restricted M^3 list in Column 2, the target's primary missile-per-target ratio in Column 3, and the sum of all missiles associated with to each target in Column 4.

Keys:	Ascending 1	Descending 2	Descending 3
BEN	Restricted M^3 List	Primary Missile-per-Target Ratio	Total Missiles
3004005100	1	1	2
3004005300	1	1	4
3004005500	1	0.5	4
3004005700	1	0.5	8
3004005900	1	0.5	12
3004006100	1	0.3	6
3004006300	1	0.3	12
3004005000	2	1	1
3004005200	2	1	3
3004005400	2	0.5	2
3004005600	2	0.5	6
3004005800	2	0.5	10
3004006000	2	0.3	3
3004006200	2	0.3	9

Table 9. Sorted Launch Area Target List

Aggressive allocation sorts the launch area target list ascending by M^3 list, descending by primary missile-per-target ratio, and descending by total number of missiles.

Whereas conservative allocation assigns all tasks to firing units with spread ship scoring, aggressive allocation assigns primary and/or ready-spare task parts based on the number of unassigned TLAMs onboard a firing unit and whether that firing unit is expend or spread. Expend firing units are considered for allocation in decreasing order of the number of unassigned TLAMs they have on board, and then by the same descending key for spread firing units. Backup task parts and ghost tasks are still assigned as with conservative allocation. We repeat the same *half-module scoring* to place missiles associated with task parts in half-modules onboard a ship or the capsules and/or torpedo tubes onboard a submarine. Figure 11 depicts aggressive allocation.

After aggressive allocation, one-complement slides and interchanges improve the predesignation to local optimality. A one-complement slide moves a task part from one firing unit to an unassigned TLAM on a different firing unit. A one-complement interchange switches task part assignments between assigned TLAMs on different firing units.

Objective values remain invariant for many slides and interchanges. For efficiency, we implement only slides and interchanges that may locally improve our objectives. Specifically, one-complement slides can only improve the following objectives: (i) reduce the number of employed penalty firing units, or (ii) increase the number of primary task parts assigned to expend firing units, or (iii) level the TLAM inventories among ships and submarines remaining in the launch area. Our one-complement interchanges can only improve: (i) spread of primary and backup task parts among ships and submarines, or (ii) decrease in use of over-endowed missiles. We have not yet incorporated the one-complement interchange for improving the weighted salvo size.

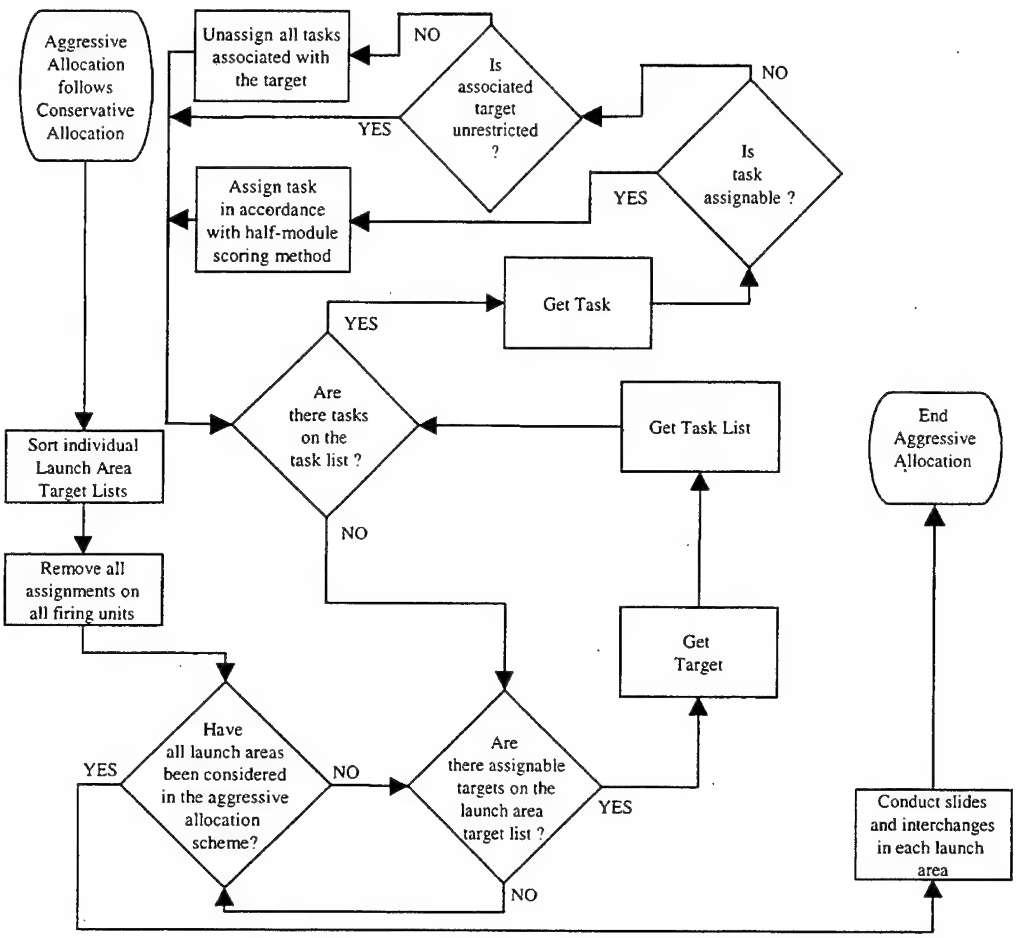

Figure 11. Aggressive Allocation

Aggressive allocation follows conservative allocation, retaining the targets assigned to each launch area and the firing units on the firing units list associated with each launch area.

III. RESULTS

A. IMPLEMENTATION AND SCENARIO DESCRIPTIONS

We implement this heuristic in Java Version 2 [Java, 1999] and run it on a 550 MHz personal computer with a Pentium III processor. Twelve Java classes, approximately 400 methods, and over 7250 lines of code compose the program.

Kirk and Hodge test their models with six scenarios developed by the Naval Surface Warfare Center, Dahlgren Division. Variations of Scenarios 1, 2, and 5 exercise user preferences and are represented by an alphanumeric code, (e.g., 1A, 1B, 2A). We add six new scenarios to test new model features for submarines, ghost tasks, and restricted and manually prioritized targets.

Each scenario has different classes of ships and submarines containing a standard loadout of TLAM variants. A Ticonderoga class cruiser (Figure 12) is loaded with 16 block-II C and 16 block-III C TLAMs. On block-II C TLAM is loaded in the first cell of every odd-numbered half-module and one block-III C TLAM is loaded in the first cell of every even-numbered half-module. Each ship in the Ticonderoga class is loaded with a total of 32 TLAMs.

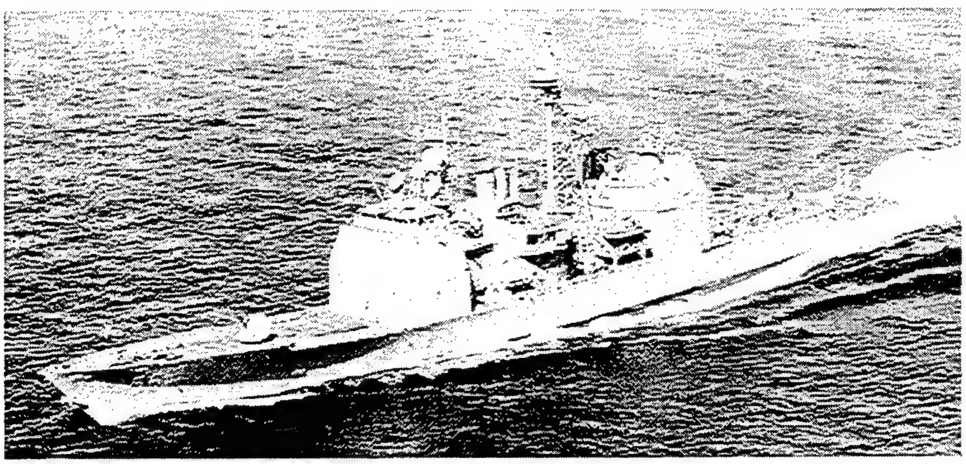

Figure 12. USS SAN JACINTO (CG-56) [U.S NAVY 1999a]

A Ticonderoga class cruiser is loaded with 16 block-II C and 16 block-III C TLAMs. On block-II C TLAM is loaded in the first cell of every odd-numbered half-module and one block-III C TLAM is loaded in the first cell of every even-numbered half-module. Each ship in the Ticonderoga class is loaded with a total of 32 TLAMs.

An Arleigh Burke class destroyer possesses a loadout similar to that of a Ticonderoga class cruiser. An Arleigh Burke class destroyer (Figure 13) is loaded with 12 block-II C and 12 block-III C TLAMs. One block-II C TLAM is loaded in the first cell of every odd-numbered half-module and one block-III C TLAM is loaded in the first cell of every even-numbered half-module. Each ship in the Arleigh Burke class is loaded with a total of 24 TLAMs.

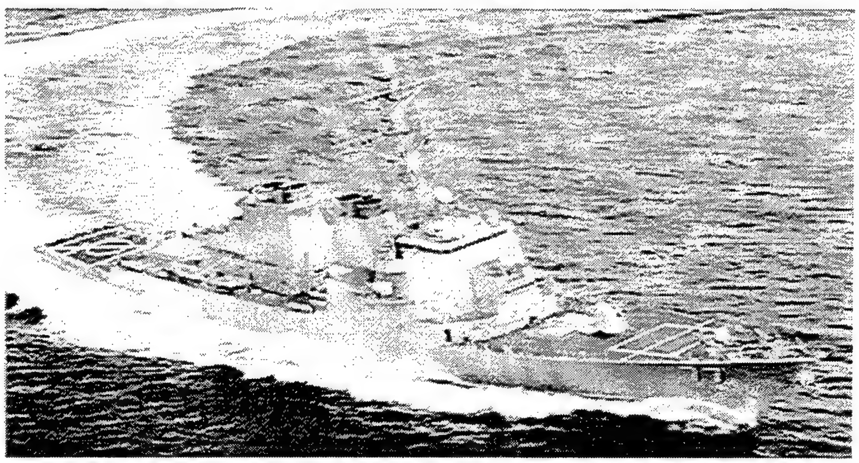

Figure 13. USS O'KANE (DDG-77) [U.S NAVY 1999b]

An Arleigh Burke class destroyer is loaded with 12 block-II C and 12 block-III C TLAMs. One block-II C TLAM is loaded in the first cell of every odd-numbered half-module and one block-III C TLAM is loaded in the first cell of every even-numbered half-module. Each ship in the Arleigh Burke class is loaded with a total of 24 TLAMs.

A Spruance class destroyer is loaded with 31 block-II C TLAMs and 30 block-III C TLAMs (Figure 14). In every half-module except the one containing the crane, the first two cells of each odd-numbered half-module are loaded with block-III C TLAMs and the last two cells are loaded with block-II C TLAMs. The first two cells of each even-numbered half-module are loaded with block-II C TLAMs and the last two cells are loaded with block-III C TLAMs. The crane half-module is loaded with a block-II C TLAM. Each ship in the Spruance class is loaded with a total of 61 TLAMs (Figure 15).

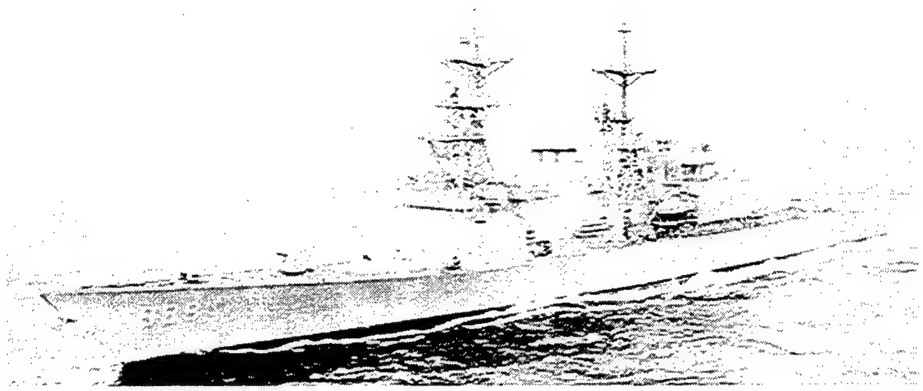

Figure 14. USS THORN (DD-988) [U.S NAVY 1999c]

A Spruance class destroyer is loaded with 31 block-II C TLAMs and 30 block-III C TLAMs. Each ship in the Spruance class is loaded with a total of 61 TLAMs.

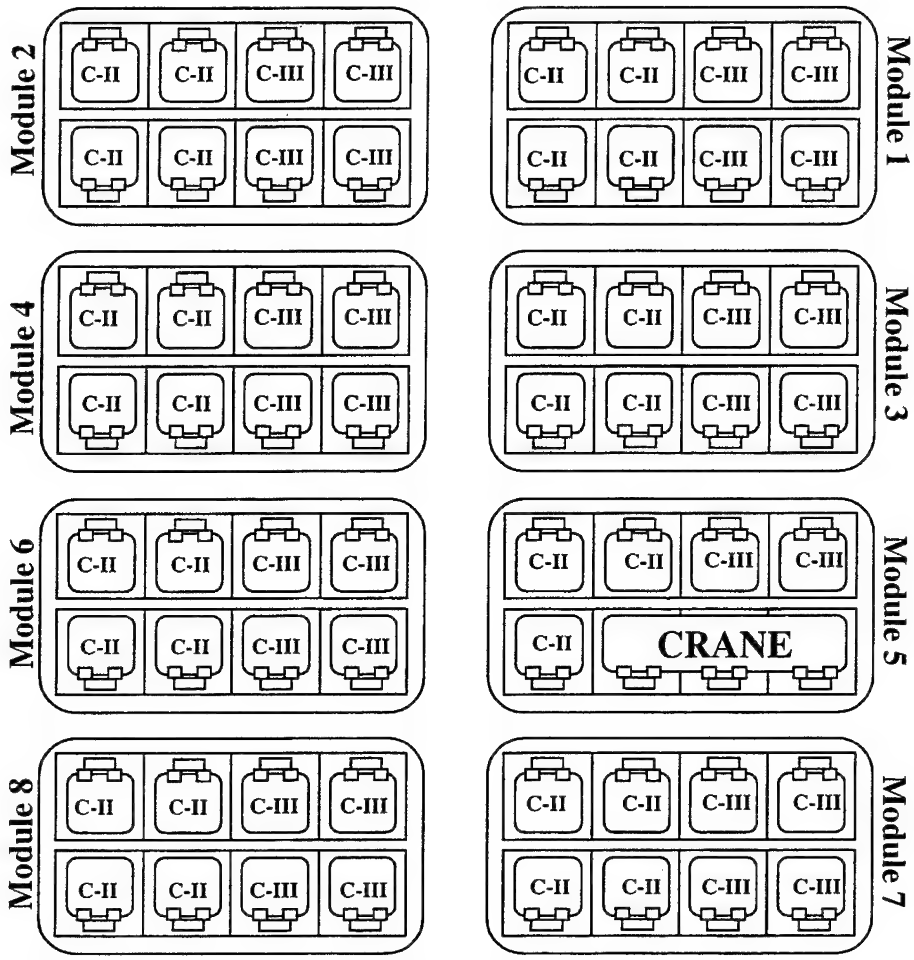

Figure 15. Spruance Class Destroyer TLAM Loadout

In every half-module except the one containing the crane, the first two cells of each odd-numbered half-module are loaded with block-III C TLAMs and the last two cells are loaded with block-II C TLAMs. The first two cells of each even-numbered half-module are loaded with block-II C TLAMs and the last two cells are loaded with block-III C TLAMs. The crane half-module is loaded with a block-II C TLAM. Each ship in the Spruance class is loaded with a total of 61 TLAMs.

Our new scenarios include Los Angeles class submarines with an installed CLS (Figure 16).

Figure 16. USS GREENVILLE (SSN-772) [U.S NAVY 1999d]

A Los Angeles class submarine is loaded with a total of 24 TLAMs, 12 in the CLS capsules and 12 loadable missiles in the torpedo room.

Figure 17 illustrates a forward, cutaway view of a Los Angeles class submarine torpedo room. In the figure, the torpedo tubes are denoted by Arabic numerals and are shaded. The remaining circles represent ordnance stored in the torpedo room. Three types of ordnance are illustrated: torpedoes (TOR), block-II C TLAMs (II-C), and block-III C

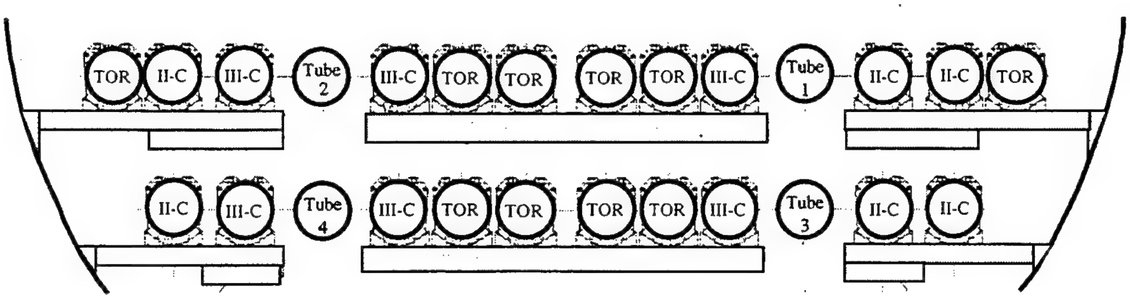

Figure 17. Forward Cutaway View of a Los Angeles Class Submarine Torpedo Room

In the figure, the torpedo tubes are denoted by Arabic numerals and are shaded. The remaining circles represent ordnance stored in the torpedo room. Three types of ordnance are illustrated: torpedoes (TOR), block-II C TLAMs (II-C), and block-III C TLAMs (III-C).

TLAMs (III-C). A Los Angeles class submarine is loaded with six block-II C TLAMs and six block-III C TLAMs in the torpedo room to fire from the torpedo tubes. Figure 18 illustrates the CLS loadout for a Los Angeles class submarine. Six of the CLS capsules are loaded with block-II C TLAMs and the other six are loaded with block-III C TLAMs. A Los Angeles class submarine is loaded with a total of 24 TLAMs.

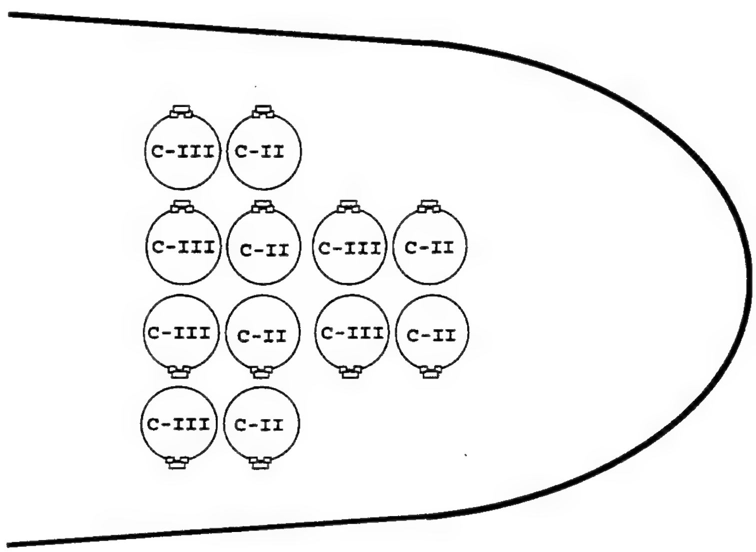

Figure 18. Loadout of the Capsule Launching System

Six of the CLS capsules are loaded with block-II C TLAMs and the other six are loaded with block-III C TLAMs.

The original six Dahlgren scenarios are composed from a subset of 104 tasks that are separated into eight task groups of consisting of thirteen tasks each. Each group consists of four tasks with only a primary task part, one task with a primary and a ready-spare task part, one task with a primary and a backup task part, and seven tasks with primary, ready-spare, and backup task parts. Each task has an associated earliest time to launch (ETL), latest time to launch (LTL), and M^3 list. We assume that the ETL and LTL coincide. In reality, these two times would differ by, perhaps, hours. We assume a

45 minute alignment time for TLAMs fired from all units. Tasks that conflict with each other based on their launch times and alignment times cannot be assigned to the same half-module, capsule, or torpedo tube. All tasks require either a block-III C TLAM, or either a block-II C or a block-III C TLAM. Because the block-III C TLAMs are more capable than block-II C TLAMs, it is desirable to use a block-II C TLAM if either weapon can be used. Table 10 shows the attributes for each task.

		ETL/LTL		M^3 List	
Group	Tasks	Day	Time	Block - II	Block - III
1	1-10	232	0000	yes	yes
	11-13	232	0030	yes	yes
2	14-23	232	0100	yes	yes
	24-26	232	0130	yes	yes
3	27-36	232	0200	no	yes
	37-39	232	0230	no	yes
4	40-49	232	0300	no	yes
	50-52	232	0330	no	yes
5	53-62	232	0400	yes	yes
	63-65	232	0430	yes	yes
6	66-75	232	0500	yes	yes
	76-78	232	0530	yes	yes
7	79-88	232	0600	yes	yes
	89-91	232	0630	yes	yes
8	92-101	232	0700	yes	yes
	102-104	232	0730	yes	yes

Table 10. Group, ETL, LTL, and M^3 Requirements for All Tasks

Each group consists of four tasks with only a primary task part, one task with a primary and a ready-spare task part, one task with a primary and a backup task part, and seven tasks with primary, ready-spare, and backup task parts. Each task has an associated earliest time to launch (ETL), latest time to launch (LTL), and M^3 list. We assume a 45 minute alignment time for TLAMs fired from all units. Tasks that conflict with each other based on their launch times and alignment times cannot be assigned to the same half-module, capsule, or torpedo tube. All tasks require either a block-III C TLAM, or either a block-II C or a block-III C TLAM.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Scenario	CG	DDG	DD	SSN	Primary	Ready-spare	Backup	Ghost	Spread Primary	Spread Backup	Restricted Targets	Number of Expend Units	Number of Launch Areas	Units with an Employment Penalty
1	2	1	1	0	13	8	8	0	Y	N	0	0	1	1 CG
1A	2	1	1	0	13	8	8	0	N	N	0	1	1	NONE
1B	2	1	1	0	13	8	8	0	N	Y	0	0	1	NONE
2	2	1	1	0	26	16	16	0	N	N	0	0	1	1 CG
2A	2	1	1	0	26	16	16	0	Y	N	0	0	2	1 CG
3	2	1	1	0	52	32	32	0	Y	N	0	0	1	1 CG
4	2	1	1	0	65	40	40	0	Y	N	0	0	1	1 CG
5	3	2	2	0	78	48	48	0	Y	N	0	0	1	1 CG
5A	3	2	2	0	78	48	48	0	Y	N	0	3	1	1 CG
5B	3	2	2	0	78	48	48	0	Y	N	0	0	1	2 CG, 1 DD
6	3	2	2	0	104	64	64	0	Y	N	0	3	1	1 CG
7	2	1	0	1	13	8	8	0	Y	N	0	0	1	1 CG
7A	2	1	0	1	13	8	8	0	N	N	0	1	1	NONE
7B	2	1	0	1	13	8	8	0	N	Y	0	0	1	NONE
8	2	1	1	0	9	8	8	4	N	N	0	0	1	1 CG
8A	2	1	0	1	9	8	8	4	N	N	0	0	1	1 CG
9	2	1	1	0	13	8	8	0	Y	N	4	0	1	1 CG
9A	2	1	0	1	13	8	8	0	Y	N	4	0	1	1 CG
10	2	1	1	0	13	8	8	0	Y	N	0	0	1	1 CG
10A	2	1	0	1	13	8	8	0	Y	N	0	0	1	1 CG
11	0	0	1	0	13	8	8	4	Y	N	4	0	1	NONE
12	2	2	2	2	74	48	48	4	Y	N	4	0	2	1 CG

Table 11. Scenario Attributes

Note: CG refers to a Ticonderoga class cruiser. DDG refers to an Arleigh Burke class destroyer. DD refers to a Spruance class destroyer. SSN refers to a Los Angeles class submarine with an installed CLS.

Scenario 7 (and its variants) is similar to Scenario 1 (and its variants), except that we replace the Arleigh Burke class destroyer with a Los Angeles class submarine with a CLS and four capable torpedo tubes. This substitution reduces the firing unit salvo size from 24 to 16.

Scenario 8 (and its variants) is similar to Scenario 1 (and its variants), except that the four tasks consisting only of a primary task part are replaced with four ghost tasks. Each ghost task provides redundancy for three primary task parts and retains the attributes of the original four primary task parts with respect to the number of missiles, the ETL, the LTL, and the M^3 list.

In Scenario 9 (and its variants), all attributes are similar to those in Scenario 1 (and its variants), except four targets are designated as restricted targets; as in Scenario 1, the task lists of these four targets consist of two tasks each; the first task consists of primary, ready-spare, and backup task parts while the second task consists of only a primary task part. Both of the tasks on each task list share the same ETL, LTL and M^3 list. Scenarios 1 through 9 contain task parts with only one associated missile.

Scenario 10 (and its variants) is similar to Scenario 1 (and its variants) except that six tasks require multiple missiles; specifically, four tasks consist of a single primary task part that requires two missiles, one task consists of a primary and ready-spare task part, each requiring two missiles, and one task consists of a primary and backup task part, each requiring two missiles.

Scenario 11 contains manually prioritized targets that would not necessarily be ordered near the top of the target list; however, because of their priority, they are considered first.

Scenario 12 simultaneously illustrates the inclusion of restricted targets, ghost tasks, submarines, and a manually-prioritized target list, and uses a large task set and two distinct launch areas.

B. RESULTS

We use the eight Kirk objectives described in Chapter I, Section H, to evaluate the task-to-firing unit allocations. These are hierarchical objectives, but we view the values of each as informative. We use Kirk's near-optimal solutions to evaluate our heuristic solution.

Table 12 gives results for Scenarios 1 through 6. Note that we include the sense of the objective (i.e., maximization or minimization) in the first row of the table. Our heuristic yields results superior to Hodge and relatively close to Kirk. This heuristic runs as quickly as Hodge's heuristic and much more quickly than Kirk's integer program.

Both Kirk's and our objectives are the same for Scenarios 1 and 1A. Our results outperform Kirk's results in Scenarios 1B, 4, and 5. The key breaks occur in Objectives 6, 4 and 3, respectively. Kirk's results outperform our results in Scenarios 2A, 3, 4, 5, 5B, and 6. The key breaks all occur in Objective 3, except for Scenario 3, in which the break occurs in Objective 2, and Scenario 6, in which the break occurs in Objective 7.

Objective	1 (Min)	2 (Min)	3 (Max)	4 (Min)	5 (Max)	6 (Max)	7 (Min)	8 (Min)	
Scenario	Unassigned Task Parts	Penalty Units	Primary Missiles Assigned to Expend Units	Sum Deviation	Units with Primary Missiles	Units with Backup Missiles	M3 Positions Pri/Rsp/Bu/Gho	Weighted Maximum Salvo	Solution Time (Seconds)
1 HR (Kirk)	0	0	N/A	34	3	N/A	13/8/8/0	160	26
1 Heuristic (Hodge)	0	0	N/A	40	2	N/A	13/8/8/0	172	2
1 Heuristic	0	0	N/A	34	3	N/A	13/8/8/0	160	2
1A HR (Kirk)	0	N/A	10	8.67	N/A	N/A	13/8/8/0	160	34
1A Heuristic (Hodge)	0	N/A	9	8	N/A	N/A	13/8/8/0	173	2
1A Heuristic	0	N/A	10	8.67	N/A	N/A	13/8/8/0	160	2
1B HR (Kirk)	0	N/A	10	8.67	N/A	2	13/8/8/0	160	36
1B Heuristic (Hodge)	0	N/A	9	8	N/A	1	13/8/8/0	173	2
1B Heuristic	0	N/A	10	8.67	N/A	3	13/8/8/0	160	2
2 HR (Kirk)	0	0	N/A	23	3	N/A	26/16/16/0	157	335
2 Heuristic (Hodge)	0	0	N/A	32	3	N/A	31/18/19/0	158	3
2 Heuristic	0	0	N/A	13.5	2	N/A	30/19/22/0	162	3
2A HR (Kirk)	0	1	N/A	42.5	2	N/A	26/20/16/0	146	103
2A Heuristic (Hodge)	0	1	N/A	44.5	2	N/A	29/16/16/0	156	8
2A Heuristic	0	1	N/A	44.5	4	N/A	29/16/16/0	141	4
3 HR (Kirk)	0	0	N/A	15.5	3	N/A	52/32/32/0	129	1625
3 Heuristic (Hodge)	0	1	N/A	15	4	N/A	52/32/32/0	133	22
3 Heuristic	0	1	N/A	1.5	3	N/A	52/32/32/0	130	5
4 HR (Kirk)	0	1	N/A	0	4	N/A	65/52/40/0	127	6133
4 Heuristic (Hodge)	0	1	N/A	30	4	N/A	76/41/40/0	110	40
4 Heuristic	0	1	N/A	16	4	N/A	77/40/40/0	107	10
5 HR (Kirk)	0	0	N/A	11.4	4	N/A	78/50/48/0	268	10976
5 Heuristic (Hodge)	0	0	N/A	46.4	6	N/A	89/54/52/0	253	36
5 Heuristic	0	0	N/A	25.4	6	N/A	83/53/54/0	252	10
5A HR (Kirk)	0	0	65	34	5	N/A	78/62/48/0	242	2356
5A Heuristic (Hodge)	0	0	44	25	6	N/A	83/52/48/0	250	36
5A Heuristic	0	0	73	40	4	N/A	85/48/56/0	227	10
5B HR (Kirk)	0	1	N/A	21.4	4	N/A	78/52/48/0	268	34340
5B Heuristic (Hodge)	0	1	N/A	38.8	5	N/A	90/53/55/0	251	87
5B Heuristic	0	1	N/A	35.1	5	N/A	90/53/55/0	240	16
6 HR (Kirk)	0	0	69	24	6	N/A	124/84/78/0	209	261
6 Heuristic (Hodge)	0	0	66	35	6	N/A	128/82/80/0	219	56
6 Heuristic	0	0	69	24	6	N/A	129/76/79/0	201	7

Table 12. Results for Scenarios 1-6

(HR) optimization and the successive heuristics are compared for the same scenarios. Kirk's eight hierarchical objectives are evaluated for each predesignation. Outlined boxes indicate key breaks that determine the winner for each scenario, highlighted by a dark grey box.

Scenarios 7 through 12 demonstrate the inclusion of military-oriented features, i.e., restricted targets, ghost tasks, submarines, and a manually-prioritized target list.

Our results for each Scenario 7 variation are comparable to the corresponding Scenario 1 variation. The difference in the maximum salvo between the replaced Arleigh Burke class destroyer and the substituted Los Angeles class submarine explains the changes in some of the objective values.

In Scenario 8, all ghost tasks are assigned to units with excess planning capacity, i.e., the Spruance and Arleigh Burke class destroyers and the Los Angeles class submarine. The Arleigh Burke class destroyer has a greater excess planning capacity than the Spruance class destroyer and is therefore allocated a greater number of ghost tasks. The Ticonderoga class cruiser has no excess planning capacity and is not allocated any ghost tasks. Objective values are comparable to those obtained in Scenario 1; small deviations result from overriding factors relevant to ghost task assignment.

Scenario 9 incorporates restricted targets. In each scenario, only two firing units are assigned tasks associated with a restricted target. Note that a second firing unit must be employed to accommodate backup task parts. Objective values are the same as those obtained in Scenario 1.

The objective values obtained in Scenario 10 are comparable to Scenario 1 if the additional number of missiles associated with the six tasks is considered.

Scenario 11 consists of a single ship and targets with tasks requiring more missiles than can be assigned; this scenario illustrates manual prioritization of a target list. The unassigned targets are low priority and possess fewer task points than the assigned targets, which places these unassigned targets lower on the target list.

Scenario 12, the large-scale scenario containing all four military-oriented features, allocates all targets in the two separate launch areas without using the single penalty firing unit. In addition, the protocol for restricted target and ghost task assignment is followed, and the allocations and objective values are reasonable for a scenario of this size and type.

Objective	1 (Min)	2 (Min)	3 (Max)	4 (Min)	5 (Max)	6 (Max)	7 (Min)	8 (Max)	
Scenario	Unassigned Task Parts	Penalty Units	Primary Missiles Assigned to Expend Units	Sum Deviation	Units with Primary Missiles	Units with Backup Missiles	M^3 Positions	Weighted Salvo Size	Solution Time (Seconds)
7 Heuristic	0	0	N/A	34	2	N/A	13/8/8/0	160	2
7A Heuristic	0	0	10	34.67	N/A	N/A	15/8/10/0	152	5
7B Heuristic	0	0	10	8.67	N/A	3	13/8/8/0	160	2
8 Heuristic	0	0	N/A	36	N/A	N/A	9/8/8/4	162	2
8A Heuristic	0	0	N/A	36	N/A	N/A	9/8/8/5	162	2
9 Heuristic	0	0	N/A	34	3	N/A	13/8/8/0	160	3
9A Heuristic	0	0	N/A	34	N/A	3	13/8/8/0	160	3
10 Heuristic	0	0	N/A	39	3	N/A	28/9/9/0	147	3
10A Heuristic	0	0	N/A	37	3	N/A	28/11/11/0	147	3
11 Heuristic	7	0	N/A	0	1	N/A	10/6/0/0	162	1
12 Heuristic	0	0	N/A	43	7	N/A	96/52/55/4	256	12

Table 13. Results for Scenarios 7-12

Scenarios 7 through 12 demonstrate the inclusion of the military-oriented features, i.e., restricted targets, ghost tasks, submarines, and a manually-prioritized target list. These predesignations have been carefully audited, and they are acceptable.

IV. CONCLUSIONS AND EXTENSIONS

A. GENERAL

Our heuristic suggests predesignations much faster than Kirk's integer program. We provide Tomahawk Strike Coordinators with a tool they can use in an operational setting. We enhance the applicability of Hodge's heuristic by adding tasks that are restricted on a per-target basis, incorporating ghost tasks, including submarines, and allowing the TSC to manually prioritize all or part of the target list.

Because we myopically allocate tasks to firing units presented in static, lexicographically ordered lists, the heuristic can and will yield poor results if limitations of myopia are not recognized and addressed. We use one-complement slides and interchanges to ensure that we do not suggest a predesignation that can be trivially improved. Although one-complement slides have improved our predesignation, one-complement interchanges have not. This implies that our solutions for these instances are intrinsically locally optimal with respect to one-complement interchange. Nonetheless, we retain this one-complement interchange to preclude trivially-improvable solutions that could arise in other scenarios. Even one trivially-flawed solution loses the faith and confidence of the planner, and this faith and confidence would be difficult to regain.

B. RECOMMENDATIONS

The objectives we use to guide the heuristic, with the exception of minimizing unassigned task parts, using the least capable missile possible, and maximizing weighted salvo size, do not represent any official TLAM predesignation guidance. Official guidance on these objectives must be obtained from the Navy prior to introducing this

heuristic into the fleet. The TSC needs to be able to manually prioritize the objectives based on his experience.

C. EXTENSIONS

[Fennemore, 2000] suggests that the heuristic should allow manual guidance. Specifically, the TSC would nominate the best choice of firing platform for the allocation of a particular task. The TSC would then accept the automated recommendation or override and manually assign the task.

Alternately, we suggest proposing a complete allocation to the TSC, who can then modify the plan, as desired, or provide guidance for its revision. The heuristic could then completely reallocate the targets based on the TSC's advice.

If the heuristic is unable to make a complete allocation of tasks to firing units, the heuristic might suggest options to eliminate the unassigned tasks, e.g., by consolidating redundancies from ready-spare and backup task parts into ghost tasks, or changing the ETL and/or LTL of a task.

The myopic, single-pass heuristic incorporates only limited context-dependent backtracking. Thus, the quality of its allocations is wholly dependent on the sequence of the presented launch area list, target list, and task list. The attributes of each scenario can likely be used to suggest scenario-specific sort keys. For example, gauges of missile-rich or missile-poor targets, target-rich or target-poor launch areas, and so forth, might be used to induce an attractive sort key set.

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